PHARMACEUTICAL ENGINEERING

Principles and Practice

Unit Operations

Abridged with PCI Syllabus of B.Pharmacy

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Former Director, Divi's Laboratories, Hyderabad)

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Preface to the Third Edition

The book entitled 'Pharmaceutical Engineering' was introduced by us in 2001. Over 16 years, this book has been patronized by teachers and students alike. This encouraged us to revise periodically and the current edition is 3rd edition. The 2nd edition of pharmaceutical engineering was available in two volumes (I and II), in tune with the syllabi prescribed by several universities in two semesters and on the lines of syllabus prescribed by AICTE.

This edition is framed as per the prescribed syllabus of the Pharmacy Council of India (vide no. 6, 7 and 8 of Bachelor of Pharmacy (B.Pharm) course regulations 2014, which is applicable throughout India. The syllabus identified only 14 chapters and accordingly modified. These are: Industrial Processing & Basic Principles, Flow of Fluids, Size Reduction, Size Separation, Flow of Heat, Evaporation, Distillation, Drying, Mixing, Filtration, Centrifugation, Materials of Construction, Corrosion and Transportation of Solids.

The present attempt provides ample scope for expanding and thorough revision of the content area. Efforts were made to present the information in lucid manner. In this edition, objectives are included at the beginning of the chapter and summary is appended at the end of each chapter. The format and importance of the earlier editions is maintained for the familiarity and readability. Comments are answered. Over the years, the experience accrued over these books made to have a fresh look at this book. Special emphasis was maintained on the lines of expectations.

1. Application of principles
2. A number of illustrations on the lines of concept mapping
3. Comment type questions and answers
4. MCQs and key and question bank

Suggestions and criticism are welcome from teachers and students.

Hyderabad
22nd October 2018

Authors

Preface to the First Edition

Pharmaceutical Engineering is concerned with the study of industrial processes required to convert raw material into value added pharmaceuticals such as drugs and excipients. It is a subject of importance both to the industrial pharmacist and the undergraduate students. Over the years, students of pharmacy have been feeling the need for a simple book, yet in sufficient depth to enable them to handle industrial operations with an understanding of the principles involved therein. This book is an attempt to meet these twin objectives.

This book consists of 18 chapters: introduction to basic principles in engineering, fluid flow, liquid material transport, solid conveying, heat flow, size reduction, size separation, mixing (solids, liquids and semi-solids), filtration, centrifugation, distillation, evaporation, crystallisation, drying, humidification and dehumidification, corrosion, plant materials of construction and other related aspects of pharmaceutical industry.

This book deals with unit operations and processes utilised in the production of bulk drugs, dosage forms and biological products. There is a proper blend of physical, chemical and engineering principles. One model equipment has been selected for explaining all the principles and general working though many variations and varieties of the same may be available. Hopefully this book will provide strong foundations on the subject and for in-house training of technical personnel in the industry.

Special emphasis is laid on the following.

- Application of principles, practice and pharmaceutical examples.
- Illustrations and diagrams explaining the working of equipment.
- Units have been described in SI system.
- Question bank.

Suggestions and criticism are welcome.

Davangere
15th June, 2001

Authors

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I acknowledge the assistance of Mrs. C. Surya Pavani, M. Pharm., for reading the manuscript. I acknowledge the support extended by Mr. D.V.N. Shivrama Raju, Systems Assistant, Gokaraju Rangaraju College of Pharmacy, Hyderabad. I thank my wife, Mrs. Lakshmi Devi for her support in bringing this book.

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Hyderabad
Date: Dec 2017

C.V.S. Subrahmanyam
Senior Author

PCI Syllabus of Engineering and Division of the Chapters, Units, Pages

BP304T. PHARMACEUTICAL ENGINEERING (THEORY)

45 Hours

Scope : This course is designed to impart a fundamental knowledge on the art and science of various unit operations used in pharmaceutical industry.

Objectives : Upon completion of the course student shall be able:

1. To know various unit operations used in Pharmaceutical industries.
2. To understand the material handling techniques.
3. To perform various processes involved in pharmaceutical manufacturing process.
4. To carry out various tests to prevent environmental pollution.
5. To appreciate and comprehend significance of plant layout design for optimum use of resources.
6. To appreciate the various preventive methods used for corrosion control in Pharmaceutical industries.

COURSE CONTENT

Chapter 1—Flow of Fluids

Fluid Statics, Types of manometers, fluid dynamics, Bernouli's theorem, Reynolds number and its significance, its applications, energy losses, measurement of rate of flow of fluids (Orifice meter, venture meter, pitot tube and rotometer).

Chapter 2—Size Reduction

Objectives and mechanisms of size reduction, modes of stress applied in size reduction, classification of size reduction, factors affecting size reduction, principles, construction, working, uses, merits and demerits of equipment (hammer mill, ball mill, fluid energy mill, edge runner mill and end runner mill), selection of a mill, laws governing size reduction (theories and energy).

Chapter 3—Size Separation

Objectives, applications & mechanism of size separation, official standards for powders, sieves -sizes, modes of motion in size separation - separation principles, sieve analysis – testing of powder, construction, working, uses, merits and demerits of equipment for size separation (sieve shaker, cyclone separator, air separator, bag filter and elutriation tank).

Chapter 4—Flow of Heat

Objectives, applications and heat transfer mechanisms, mechanism of heat flow, conduction (Fourier's law, heat transfer by conduction), convection, radiation, equipment – heat exchangers and heat interchangers, steam as a heating medium, steam production – utilisation, steam traps.

Chapter 5—Evaporation

Objectives, applications and factors influencing evaporation, differences between evaporation and other heat processes, classification of evaporators, principles, construction, working, uses, merits and demerits of equipment (steam jacketed kettle, horizontal tube evaporator, climbing film evaporator, forced circulation evaporator), multiple effect evaporator, economy of multiple effect evaporator.

Chapter 6—Distillation

Basic principles and methodology of simple distillation, classification of distillation methods, simple distillation, flash distillation, fractional distillation, azetropic and extractive distillation, distillation under reduced pressure, steam distillation, molecular distillation.

Chapter 7—Drying

Objectives, applications and mechanism of drying process (theory of drying), measurements and applications of equilibrium moisture content, rate of drying curve, classification of drying equipment, principles, construction, working, uses, merits and demerits of equipment (tray dryer, drum dryer, spray dryer, fluidized bed dryer, vacuum dryer, freeze dryer), factors influencing the selection of equipment.

Chapter 9—Filtration

Objectives, applications mechanisms of filtration, theories of filtration, factors Influencing filtration, filter media and filter aids, classification of filtration equipment, laboratory scale filtration methods, principle, construction, working, uses, merits and demerits of industrial equipment (plate & frame filter, filter leaf, rotary drum filter, meta filter & cartridge filter, membrane filters and Seidtz filter.), factors affecting the selection of filtration equipment.

Chapter 10—Centrifugation

Objectives, principle and applications of centrifugation, theory of centrifugation, classification of centrifuges, laboratory centrifuges, principles, construction, working, uses, merits and demerits of industrial equipment (perforated basket centrifuge, non-perforated basket centrifuge, semi continuous centrifuge and supercentrifuge).

Chapter 11—Materials of Construction

Factors affecting the selection of materials for pharmaceutical plant construction, classification of materials for plant construction, ferrous metals, non – ferrous metals, nonmetals-inorganic, nonmetals – organic.

Chapter 12—Corrosion

Theories of corrosion, factors influencing corrosion, types of corrosion, prevention and control of corrosion,

Chapter 13—Materials Handling Systems

Belt conveyors, screw conveyors, pneumatic conveyors, chain conveyors, bucket conveyors, selection of solid transportation equipment, storage of solids.

(The PCI syllabus was expanded the theory part, but equipment prescribed was retained as mentioned above- by the authors).

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CHAPTER 1

Pharmaceutical Industrial Processing and Basic Principles

Unit Operations and Unit Processes
Unit Operations—Scientific Foundations
Units and Inter—Conversions
Dimensions—Analysis

LEARNING OBJECTIVES

After reading this chapter, the reader should be able to:

- Appreciate the importance of engineering knowledge in different areas of pharmaceutical and related industries.
- Describe the unit operations and unit processes with elements and steps involved.
- Explain the specific laws and fundamental laws governing the unit operations along with applications.
- Understand the concept of dimensions, units and systems with special attention to practice the interconversions of one system into other.
- Describe the steps involved in dimensional analysis for developing the dimensionless equation and dimensional equation.

Pharmaceutical engineering is concerned with the study of industrial processes in which raw materials are changed or converted into pharmaceutically useful products such as drugs and excipients. A wide variety of processes are involved in these conversions. Some of them are as follows.

1. **Production of dosage forms :** Conversion of drugs (chemicals as raw materials) into medicines (*dosage forms*), which are suitable for use by the patient. E.g. conversion of diclofenac sodium into dosage forms such as tablets, capsules, suspensions and injections.
2. **Production of bulk drugs :** Chemicals (raw materials) are converted into drugs. E.g. salicylic acid is acetylated to obtain acetylsalicylic acid (aspirin). This area is known as production of *bulk drugs*. Conversion of chemicals into intermediates, which in

turn are used for production of drugs in commercial scale, is also included in this area.

3. **Production of antibiotics :** Manufacture of drugs (antibiotics) using microbes with the aid of precursors is another area of interest to the pharmacist. This area is known as *fermentation technology*. E.g. penicillin G is produced using *Penicillium chrysogenum* with the aid of precursor, phenylacetic acid.
4. **Production of biologicals :** Extraction of drugs from animals, plants and minerals from native raw materials into purified (or semi-purified) products are of interest to the pharmacist. E.g. vaccines, insulin, streptokinase and recombinant DNA technology products.

Each process is developed systematically from a laboratory scale to pilot scale and finally to an industrial scale. In each case, process is undertaken by employing a number of equipment. The areas of interest with reference to equipment are:

- design
- fabrication
- assembly
- operation
- maintenance

Similarly, each process has to be followed scrupulously in terms of:

- effectivity
- efficiency
- validity
- safety
- economy

Effectiveness refers to the quality of what is to be actually accomplished. *Efficiency* means accomplishing tasks with a minimum of wasted material, time and money. In the popular management cliché, efficiency is doing things right, while effectiveness is doing right things.

Validation is defined as a procedure that demonstrates the ability of consistently producing a product with the established specifications under ideal conditions.

Safety refers to the protection of products, personnel and factory. Prevention of accidents and protection from fire constitute important aspects. Sufficient care should be exercised so that human factor is removed from the hazards by making protection a permanent and automatic.

Economy refers to the protection of factory from financial problems. The industrial activity essentially involves the conversion of raw materials into value added products. The steps are initiated for the optimization of parameters for an operation and process, so that economy works out for the factory as well as customer (or consumer). Standard Operating Procedures (SOPs) are helpful to obtain a quality product coupled with economy.

Therefore, a broad understanding of the basic principles involved in a process, knowledge about the construction, working and skills in handling them are of vital importance. This chapter provides the basic information and prerequisites that are necessary for understanding pharmaceutical engineering.

UNIT OPERATIONS AND UNIT PROCESSES

Normally, every process involves a series of steps. Each step is performed individually. This approach is an economical way of organizing a given task.

Unit Operations

Each chemical process frequently consists of a fewer number of distinct individual steps. Each step is called *unit operation*.

Each unit operation is based on one type of scientific principle. A few examples of unit operations and underlying principles are listed below.

Drying : It is a unit operation used to remove liquid or moisture from solids by evaporation with the aid of heat. For example, drying process is employed to remove excess moisture (above equilibrium moisture content) from the wet granules in the production of tablets.

Size reduction : This is a unit operation in which drugs (vegetable or chemical origin) are reduced to smaller pieces, coarse particles or fine powder. This process is extensively used in the manufacture of talcum powders and tooth powders (cosmetic industry).

Distillation : It is a unit operation of converting liquid into vapour by heating and reconverting vapour again into liquid by condensing the vapour. This unit operation is used for obtaining essential oils from various parts of the plants. E.g. lemon-grass oil (perfume industry).

Evaporation : It is a unit operation which involves free escape of vapour from the surface of a liquid below its boiling point. For example, evaporation technique is extensively used for concentrating the sugar cane juice in the manufacture of sugar (sugar industry).

The **advantage** is that each unit operation is a common technique and employed in diverse chemical and pharmaceutical industries. For example, the operation of mass transfer is involved in humidification, evaporation, distillation, extraction and drying. The unit operation of drying is used in the following industries.

(1) Pharmaceutical industry : In the production of tablets, the powdered mass is converted into wet mass, which is subsequently dried in order to obtain free flowing dry granules.

In the manufacture of herbal drug extracts, a large number of plants are used. The plant extracts are dried in order to extend the shelf life. Otherwise, the extract may deteriorate. For example, in the preparation of belladonna dry extract IP, liquid extract of belladonna is dried completely. Otherwise it gets deteriorated.

(2) Food industry : Grapes, cashew, almonds and other types of fruits are dried to obtain dry fruits. These products have extended storage life.

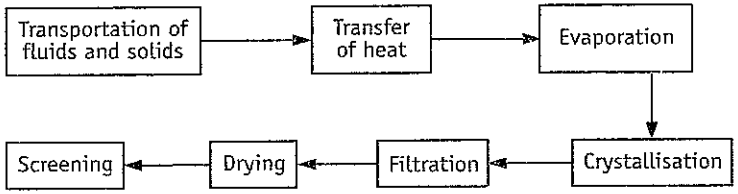
(3) Sugar industry : The crystals of sugar are dried to remove residual water, so that the sugar remains dry and free flowing.

Unit operations are based on both science and experience. The theory and practice must be combined judiciously for achieving proficiency in handling equipment.

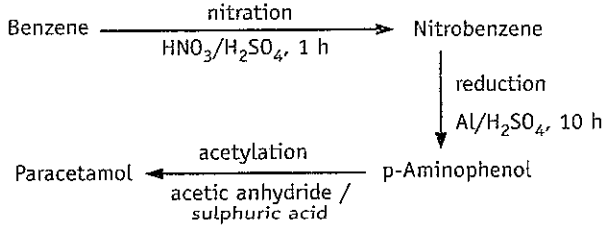
Unit Processes

Unit process is defined as the one in which several unit operations are combined in a sequence to achieve the objectives of a chemical or physical process.

Unit process-Physical process : Consider the example of manufacture of common salt. The unit operations involved are:



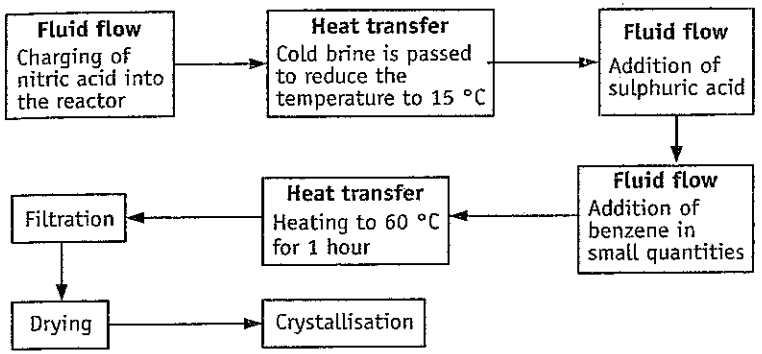
Unit process—Chemical process : Consider the production of paracetamol from benzene.



Sequence of reactions for the production of paracetamol (or acetaminophen).

In the above process, three unit processes are involved. These are nitration, reduction and acetylation. Each unit process is in turn made of

a number of unit operations. For example, in the nitration of benzene to nitrobenzene, the unit operations involved are:



These examples illustrate that unit operations are largely used to conduct the physical steps such as:

1. Preparation of the reactants,
2. Separation and purification of the products,
3. Recycling of the unconverted reactants,
4. Controlling of the energy transfer into or out of the chemical reactor.

Thus, several steps are carried in a sequential order to achieve a process efficiently and economically.

Comment 1-1. What is the difference between unit operation and unit process?

UNIT OPERATIONS — SCIENTIFIC FOUNDATIONS

A large number of unit operations are simultaneously handled in a chemical process. Hence, the knowledge of the elementary physical and chemical laws (Figure 1-1) is essential for the application of scientific principles and techniques. Some of these laws are:

Basic laws	:	Law of conservation of matter. Law of conservation of energy.
Special laws	:	Universal gas laws (Ideal gas equation). Dalton's law of partial pressures.

Special laws are discussed in detail in different books mentioned in bibliography. The basic laws are highlighted in Figure 1-1.

Basic Laws

The general laws of conservation can be applied to any process, in engineering as:

(a) Material balance (b) Energy balance

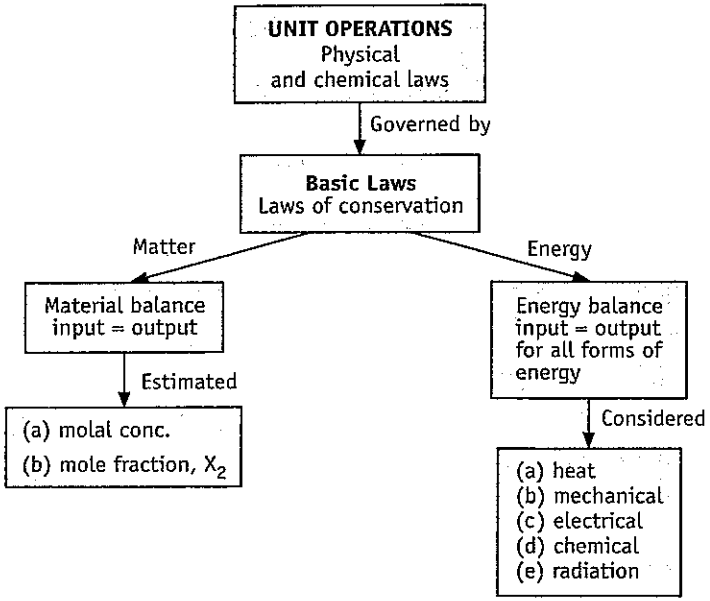


Figure 1-1. Scientific foundations in unit operations. Basic laws are included.

Material balance : *The law of conservation of matter* states that material cannot be destroyed or created, it can be changed from one form to another.

In other words, the material entering a process must either accumulate or leave the process. The given input must be accounted for an output. The principle of material balance can be applied to an equipment, or to the entire process or any part of it. A simple account of material balance.

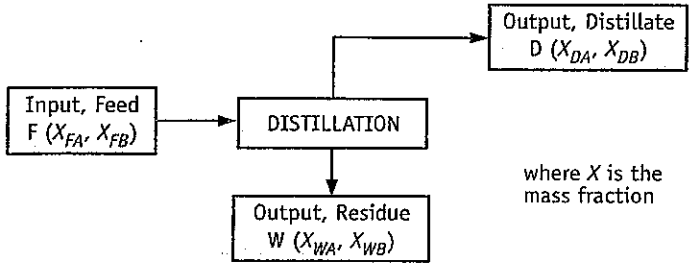
INPUT		OUTPUT		
Amount of raw materials	=	Amount of changed materials	+	Amount of unchanged materials

Radioactive process is an exception because it does not obey the material balance calculations.

Advantages : The mass balance calculations can provide information such as yield value (practical and theoretical) and percent recovery. Currently, validation of processes and equipment has become important in the certification of International Organisation for Standardisation (ISO). Mass balance calculations have assumed central place in the current industrial development.

Estimation of material balance – Physical process : In addition to overall material balance, it is also possible to write a balance expression

for each individual material entering or leaving a process. In a physical change, balance can be written for each component in distillation.



The overall material balance for distillation process:

Feed (F) = Distillate (D) + Residue (W)

Component A : The material balance is—

$$F \,.\, X_{FA} = D \,.\, X_{DA} + W \,.\, X_{WA}$$

Component B : The material balance is—

$$F \,.\, X_{FB} = D \,.\, X_{DB} + W \,.\, X_{WB}$$

Similarly, balanced equations can be written for each element in a chemical reaction also.

Tie substance : A material is called *tie substance*, if the material that comes into the process in just one stream and leaves unchanged in only one stream. The following examples illustrate the concept.

Unit operation	*Tie substance*
Evaporation	Dissolved solid
Drying	Bone dry material
Burning of coal in furnace	Ash

Applications : If one of the components is 'tie substance' in a reaction, the unknown (other components) can be solved. The total number of equations must be equal to the total number of unknown substances. Tie substance helps in solving problems using the material balances, when chemical reaction is not involved.

Estimation of material balance – Chemical process : In a chemical reaction, material balance can be accounted by measuring the amount of all the components (constituents). Normally, the amount is expressed in concentration units; moles/litre, molal units, mole fraction units, % w/v and % w/w. Some of them are reported for ready reference.

Energy balance : *Energy* is the capacity to exert a force through a distance and manifests itself in various forms.

The unit of energy in SI system is J (Joule). The energy per unit mass is known as *specific energy*, which has the unit of J/kg. Engineering processes involve; (a) conversion of energy from one form to another (b) transfer of energy from place to place (c) storage of energy in various forms utilizing a working substance. The first law of thermodynamics is a statement of conservation of energy. It expresses the fact that energy cannot be created or destroyed, though energy can be transported from one kind to another.

The *law of conservation of energy* states that the energy output must be same as the energy input in a chemical process.

The energy balance equation must include all types of energies.

- heat
- mechanical
- electrical
- chemical
- radiation

When one kind of energy is destroyed or consumed, an equal amount of another kind must be formed.

Applications : The principle of conservation of energy is applied in a number of instances. A few of them are mentioned here.

(1) In the study of fluid flow, Bernoulli's theorem is applied, which is a special case of the law of conservation of energy.

(2) Energy is converted from one form to another. This principle is used in the working of a pump wherein kinetic energy is converted into pressure head for pumping the liquids.

(3) Energy losses due to friction can be accounted, while a fluid is flowing through pipes. It is also helpful for adopting suitable measures to reduce losses.

(4) Since efficiency and economy are important parameters for any process (chemical or physical), energy calculations and balancing have assumed importance. When energy is obtained from non-renewable sources, balancing of energy will be a critical factor.

Some Basic Concepts

Rate of a process or reaction : The rate of a reaction can be understood by studying the time course changes in the concentration. In general, rate is expressed mathematically as a differential equation.

$$\text{Rate of reaction} = \frac{dQ}{dt} = \frac{dF}{R} = \frac{\text{driving force}}{\text{resistance}} \qquad ...(5)$$

where Q = quantity being transferred or reacted
t = time
F = driving force
R = resistance

According to equation (5), the rate at which a system approaches equilibrium may be expressed as the combined effect of two factors.

(a) *Potential factor* : It indicates the driving force necessary to make (proceed) the reaction.

(b) *Resistance factor* : It indicates the capacity to impede the speed for a given potential.

In the example of heat transfer from the hotter end of the iron rod to the colder end, the driving force is the difference in temperature (Δt). At the same time, iron also offers certain amount of resistance to heat flow, on account of poor thermal conductivity.

Steady state and unsteady state : In a system, if the operating conditions are varying with time, then such a system is said to be in *unsteady state or transient state*.

For example, consider a tank of cold water. A coil in which constant pressure of steam maintained is immersed in the tank. During the heat transfer through the coil, the operating conditions such as temperature difference between the coil and water do not remain same with time. Similarly, thermal resistance between the coil and water changes with time.

A system is said to be at steady state, if the conditions do not vary with time.

For example, consider water in a pipe is flowing under two conditions. (A) Water entering the tank at constant temperature and flow rate. (B) A jacket in which steam is maintained at constant temperature surrounds the pipe. Condition may vary from section to section along the pipe, but at any one cross section, it does not vary with time.

Comment 1-2. Explain a method for calculating the yield of a product.

Comment 1-3. Which are the expressions of reactants used for evaluating mass balance of a chemical process?

Comment 1-4. Tie substance is an inert substance added to a process in order to account mass balance. True or false. Explain.

Comment 1-5. What are the principles used for accounting losses due to friction in a process?

Comment 1-6. Differentiate between equilibrium and steady state.

Upstream and Downstream Processes

Upstream stage in the production involves searching for and using new materials in the process.

The term 'upstream' relates to raw materials (initial). For example, in the petroleum industry, locating the underground (underwater oil) reserves, bringing oil to the surface, supplying the raw materials to the manufacturers are the upstream processes. Upstream generally refers to starting

materials (production). In biotechnology, upstream manufacturing is to create the environment necessary for the cell to make the target protein. It is concerned with microscope, living cells, etc. It may be understood as keeping materials ready for the production. In pharmaceutical production, API and excipients may be considered as upstream process. In the study of fluid flow, fluid entering into the measuring device is also known as upstream process.

Downstream stage in the production involves processing the materials collected during a reaction stage into a finished product.

The term 'downstream' includes the sale of products to the market or marketable state of the materials (to the end use). These have direct contact with the customers. For example, in the petroleum industry final products obtained from crude oil are converted into a product fit for selling (e.g. petrol, diesel, gas, etc.) and then selling them to the customers. Downstream is related to the finished product, therapeutic proteins, antibiotics, hormones, enzymes, alcohol, etc. Several processes are listed below.

Upstream operations	***Downstream operations***
Bacterial cell (cell bank)	Extraction, isolation
Cell growth (harvest)	Sedimentation, removal of impurities
Nutrients (media)	Distillation, precipitation, filtration
Bioreactor (production)	Crystallization
Perfusion cell culture	Centrifugation
Expression platforms	Viral reduction (in biopharmaceuticals)
Assays	Polishing (chromatography)
	Finishing

The terms 'upstream and downstream' are commonly applicable to the production industries: metals, oils, gases, biopharmaceuticals and biotechnology. In the manufacture of dosage forms, it is difficult to clearly define a particular operation as upstream or downstream, because several unit operations may be used in both the stages, e.g. mixing or blending. In biotechnology, it can be demarcated as before fermentation and after fermentation.

In the pharma industry, these terms are carefully used. For example, benzene (raw material used for the synthesis) is upstream in the paracetamol manufacturing industry. For the same industry, paracetamol is downstream. However, paracetamol (API) is upstream for the industry manufacturing paracetamol tablets, which are downstream.

Quality

Quality is the totality of features and characteristics of products or services that bear on its ability to satisfy stated or implied needs.

This term includes such attributes as the identity, strength and purity (ICH Q6A). The concept of quality has existed for many years, though its meaning has drastically changed over a period of time. Some of these changes are:

- Inspecting product to ensure for meeting the specifications.
- Statistical nature, sampling plans, process charts, control charts, etc. for maintaining the quality.
- Encompasses the entire organization, not just in the production.
- Customer driven quality, i.e. quality is built into the process.

Since all functions contribute to the product quality, all share the cost of poor quality. In 1970 and 1980s, the US industries lost market share to foreign competition. In the auto industry, manufacturers such as Toyota and Honda became major players. In the consumer-goods market, companies such as Toshiba and Sony led the way. These foreign competitors produced low-priced products with considerably high quality.

Quality is the suitability of either a drug substance or a drug product for its intended use.

Quality attributes (QAs) are referred as physical, chemical, biological and microbiological properties or characteristics of a product.

These are implied to the APIs as well as the dosage forms. The above properties are specified in the quality assurance in terms of product purity, product potency, product stability, and drug release from a dosage form. These properties guide the product and process development. For a tablet, the quality attributes are:

physical attributes,
identification,
assay,
content uniformity,
dissolution,
degradation products,
residual solvent,
water content, and
microbial limits.

All properties may not have the potential to impact product or process effectiveness. As the proverb says, The vital a few and the trivial many. Therefore, a few attributes are evaluated on associated analytical techniques. For instance, all tablets are tested for many quality attributes. But a few of them are critical and therefore important, if they are within the range. For example, disintegration should not be more than 15 min and weight variation should be within the limits. These are key attributes that the pharmacopoeia prescribes and should be within the limits.

Critical quality attributes are defined as properties or characteristics, namely physical, chemical, biological or microbiological that should be within the appropriate limit (range or distribution), in order to ensure the desired quality.

The CQAs assure the quality, safety and/or efficacy of the resulting drug *product*. All quality attributes are not critical. For example, the odour of a product may not be critical, because it may not affect the efficacy and safety. The decision of criticality is decided by the *severity of harm* does to the *safety and efficacy*. Quality can be broadly defined through machines, materials, people, processes measurements and environment.

The term *critical* describes the process step, process condition, test requirement or other relevant parameters that must be controlled within predetermined criteria to ensure that the API or drug product meets the specification for its intended use.

A product is prepared through several unit operations. Therefore, the product CQA is translated into intermediate CQA and included in all unit operations. In other words, quality is built in the process throughout the production cycle. For example, content uniformity is a critical attribute of the *product* and is verified at each stage of production, blending, granulation, drying, etc. The product attribute of content uniformity is viewed as blend uniformity (in the intermediate steps) and translated into process parameters, such as particle size distribution, load level and revolutions/min, bulk density, flowability, etc. Based on the criticality, the products are classified as high risk products, intermediate risk products and low risk products.

For conventional products (immediate release), percent dissolution of drug (80 %) in 40 min becomes critical. Some examples of the critical quality attributes are:

- A sustained release product should release the drug for prolonged period.
- The aerodynamic properties for inhaled products.
- Sterility tests for parenteral products.
- Adhesion to the skin in case of transdermal delivery systems.
- Time to float and floating time for a floating tablet.

For example, a product contains two APIs, API-1 is present to the tune of 80 % of weight of the tablet, while the API-2 has 1 % by weight. Hence API-2 becomes critical for content uniformity. It is at high risk. For achieving the critical attributes of quality, a proper knowledge of the materials and understanding the processes are essential as per the concept of quality by design (QbD). The material parameters (MAs) and process parameters (PPs) are thoroughly controlled. Thus several terms are introduced as critical impurities, critical intermediates, critical operating limits, critical process parameters, critical quality attributes, etc.

Process parameters are the input variables to the process that may affect the outcome.

A few examples of process parameters are:

- Equipment material of construction,
- Batch size (scale),
- Quality and quantities of materials (or their ratios),
- Sequence of additions/operation,
- Time, temperature, pressure, pH, stirring rate etc.
- Heating or cooling rate,
- Specific equipment settings.

In the drying operation, humidity, ambient temperature, rate of heat transfer, moisture content, particle size distribution, etc. are process parameters as these influence the downstream processes. Further process parameters are identified by specific terms so as to evaluate the process effectiveness. Terms such as key process parameters and critical process parameters are introduced.

Key process parameters (*KPP*) are defined as properties that influence product quality or process effectiveness.

For each parameter, the limits are set and maintained throughout process. Based on the limits, parameters may be identified as key or critical. Key parameter is adjustable, within a narrow range and ensures operational flexibility. A non-key parameter has a wide range although at extremities could have an impact on process performance. In the drying, moisture content and particle size distribution are the key attributes. All key parameters are important, but a few key parameters need to be maintained within a narrow range, as it affects the attributes (critical performance).

Critical process parameters (*CPP*) are the process parameters that influences the critical quality attributes (CQA) and that must be controlled with a predefined limits so as to ensure its fitness for use in subsequent steps.

Process parameters are adjustable parameters that are maintained within a narrow range in order not to affect the product critical attributes. In the drying of granules, moisture content is critical and it seriously affects the compression. Thus, moisture content is periodically analysed and ensured to be within the critical limits and then drying is stopped. Just before starting the compression step, once again moisture content of the powder mass is evaluated. Based on the attribute, the time of drying is validated for a given set of conditions. Still the moisture content needs to be analysed periodically before stopping the drying operation. The risk management and control strategy are centered round the critical quality attributes, because these should be maintained.

In each chapter, the process parameters, material attributes and critical quality attributes are reported. In a single unit operation itself, the attri-

butes vary depending on the type of equipment chosen. For example, the parameters and attributes are different to freeze drying equipment, fluidized bed dryer, trays, etc. Sometimes, additional attributes may be added for any special type of operation. For example, sterile filtration demands additional attributes along with those observed in a non-sterile filtration. In tablets, magnesium stearate is added to the blending of the ingredients before compression step. The basic parameters remain same as in those mentioned for simple solid blending (mixing).

UNITS AND INTER-CONVERSIONS

For the purpose of measurement (dimensions), three systems have been used, namely:

cgs system (centimetre-gram-second)—Also known as metric system

fps system (foot-pound-second)—Also known as British system

mks or SI (metre-kilogram-second)—Also known as metric system

The basic quantities identified for this purpose are length, mass and time. These are expressed in various ways in different systems.

The units mentioned in any system for expressing the physical quantities are known as *fundamental units or primary units*.

For example, length is expressed as centimetre in cgs system, foot in fps system and metre in mks system. The official international system of units is the SI system (Systeme Internationale d'Units) and commonly employed in engineering and science. The basic units in SI system are given in Table 1-1. Primary units are the basis for obtaining derived units.

Secondary units or derived units are the units made by the inclusion of primary units.

For example, acceleration is a secondary unit. It is expressed as length/time^2. Alternative base units are given in B part of Appendix VII.

TABLE 1-1

Basic Units in SI System

Measurement/Quantity	*Unit*	*Symbol*
Length (L)	Metre	m
Mass (m)	Kilogram	kg
Time (t)	Second	s or sec
Amount of substance	Mole	mol
Temperature	Kelvin	K
Electric current	Ampere	A
Luminous intensity	Candela	cd

Applications : It is essential to be conversant with all the systems and also their inter-conversions. In pharmaceutical engineering, it is necessary to handle a large number of physicochemical data, while selecting the right kind of materials for a process. Most of the literature data are available in the older systems such as cgs and fps systems. Therefore, it is necessary to be expert in all the systems of units.

Inter Conversions

Any quantity can be converted from one system to other by the use of conversion factors.

Conversion factor is a pure number and simply the ratio of the magnitude of the unit in one system to that of the corresponding unit in the other system.

Conversion factors are simply multiplication factors. For example, the length expressed in fps system is 10 feet. To convert it from fps to SI system, the conversion factor is 0.3048, i.e. 1 foot = 0.3048 metre.

Hence, 10 feet = 0.3048 × 10 = 3.048 metre

It is always better to make a mental-picture of a unit, which gives a large figure (i.e. number). Then the conversion factor should be applied as direct proportionality or inverse proportionality. This can be illustrated here.

In the above example, the conversion factor is 0.3048. Metre (mks system) has higher magnitude compared to feet (fps system). Therefore, metre has a small number compared to the corresponding number in feet. Hence, foot has to be multiplied by the conversion factor to get metre.

$$10 \text{ feet} = 10 \times \text{conversion factor}$$
$$= 10 \times 0.3048 = 3.048 \text{ metre}$$

Conversely, metre should be divided by conversion factor to obtain feet. For example,

$$3.048 \text{ metre} = \frac{1}{0.3048} \times 3.048 = 10 \text{ feet.}$$

Inter-conversion between SI system and cgs system is simple, because both use same standards for time and temperature. Mass can be converted from one system to the other. Some conversion factors for primary and secondary units between different systems are in Tables 1 and 2 of Appendix VIII.

Temperature is denoted in degrees by Celsius (°C), or Fahrenheit (°F) or Kelvin (K) scale. The thermodynamic temperature scale is called the Rankine scale, in which the temperature is denoted by degrees Rankine. Their relationships are given in Table 3 of Appendix VIII.

Comment 1-7. Understanding the magnitude of values is important, while applying the conversion factor. Explain.

Practice Problem 1-1. The unit of viscosity in the cgs system is the poise, which is equal to 1 dy.s/cm^2. If the fluid has a viscosity of 0.20 poise, calculate the corresponding value in SI units (Pa·s).

Solution : Data—The units are:

$$\text{Poise} = \frac{\text{dy.s}}{\text{cm}^2} = \frac{\text{g}}{\text{cm.s}}$$

The viscosity in SI units and its conversion into base units may be written as:

$$\text{Viscosity} = Pa{\cdot}s = \frac{\text{N.s}}{\text{m}^2} = \frac{\text{kg.m.s}}{\text{s}^2\text{.m}^2} = \frac{\text{kg}}{\text{s.m}}$$

The conversion factor can be determined as follows. From the conversion Table of Appendix VIII, the following factors are obtained.

$$1\text{ g} = (1/1000)\text{ kg};\ 1\text{ cm} = (1/100)\text{ m}.$$

By substituting the above terms for units

$$\frac{\text{g}}{\text{cm.s}} = \frac{(1/1000)\text{ kg}}{\text{s} \times (1/100)\text{ m}} = \frac{100\text{ kg}}{1000\text{ m s}} = \frac{1\text{ kg}}{10\text{ m.s}} = 0.1\text{ kg/m}{\cdot}\text{s}$$

$$0.20\text{ poise} = 0.2 \times 0.1\text{ Pa}{\cdot}\text{s} = 0.02\text{ Pa}{\cdot}\text{s}$$

Practice Problem 1-2. The density of talc is reported as 2.7 g/mL. Express the same in SI system (kg/m^3).

Solution : The given unit of density is g/ml to be converted to kg/m^3. g/ml is also equal to g/cm^3. From the conversion Table 1 of Appendix VIII, the following factors are obtained.

$$1\text{ g} = (1/1000)\text{ kg};\ 1\text{ cm}^3 = (1/100)\text{ m}^3.$$

The conversion factor may be obtained as follows:

$$\frac{\text{g}}{\text{cm}^3} = \frac{(1/1000)\text{ kg}}{(1/100)^3\text{ m}^3} = \frac{1000000\text{ kg}}{1000\text{ m}^3}$$

$$= \frac{1000\text{ kg}}{\text{m}^3} = 1000\text{ kg/m}^3$$

The conversion factor = 1000

$$2.70\text{ g/mL} = 1000 \times 2.7\text{ kg/m}^3 = 2700\text{ kg/m}^3$$

Practice Problem 1-3. *In the literature, mass transfer coefficients in the gas phase are often reported in terms of* lb·mol/h·ft^2·atm. Determine the conversion factor by which the above must be multiplied in order to obtain the corresponding value of kg·mol/s·m^2·Pa.

Solution : The given units — units into which converted

$$\frac{\text{lb . mol}}{\text{h . ft}^2\text{ . atm}} \qquad \frac{\text{kg . mol}}{\text{s . m}^2\text{ . Pa}}$$

From conversion Table 1 of Appendix VIII, the following conversion factors can be obtained.

$$\text{lb} = 0.4536\text{ kg};\ \text{ft}^2 = 0.093\text{ m}^2;$$

$$\text{h} = 60 \times 60\text{ s};\ \text{atm.} = 1.01325 \times 10^5\text{ Pa}.$$

Substituting the values in the equation gives:

$$\frac{\text{lb.mol}}{\text{h.ft}^2\text{.atn}} = \frac{0.4536\text{ kg.mol}}{0.093\text{ m}^2 \times 60 \times 60\text{ s} \times 1.01325 \times 10^5\text{ m}^2\text{ Pa}}$$

$$= \frac{0.4536\text{ kg.mol}}{0.093 \times 3600 \times 1.01325 \times 10^5\text{ m}^2\text{ Pa}}$$

$$= \frac{0.4536\text{ kg.mol}}{339.236 \times 10^5\text{ m}^2\text{.s.Pa}}$$

$$= 1.337 \times 10^8\text{ kg/m}^2{\cdot}\text{h}{\cdot}\text{Pa}.$$

The conversion factor for lb/ft^2·h·atm. = 1.337×10^8 kg/m^2·h·Pa.

Practice Problem 1-4. The overall coefficient of heat transfer is 200 Btu/h·ft^2·F. Convert the same into SI units [W/m^2.K].

Solution:

The given units of $\frac{\text{Btu}}{\text{h.ft}^2\text{. F}}$ into units of $\frac{\text{W}}{\text{m}^2\text{.K}}$

The Btu/s equivalent in SI units is J/s, while J/s is equal to W. Therefore, J/s is considered in place of W for obtaining conversion factor.

$$\frac{\text{Btu}}{\text{h.ft}^2\text{. F}} \text{ to } \frac{\text{J}}{\text{s.m}^2\text{.K}}$$

From the conversion Tables 1 & 3 of Appendix VIII, the following relationships can be obtained.

$$1\text{ Btu} = 1.0551 \times 103\text{ J};\ 1\text{ h} = 60 \times 60\text{ s}$$

$$1\text{ ft}^2 = 9.290 \times 10^{-2}\text{ m}^2;\ 1\ ^\circ\text{F} = (1/1.8)\text{ K}$$

Substituting the above conversion factors into the above equation gives:

$$\frac{\text{Btu}}{\text{h.ft}^2\text{. F}} = \frac{1.0551 \times 10^3\text{ J}}{60 \times 60 \times 9.290 \times 10^{-2} \times (1/1.8)\text{ s.m}^2\text{.K}}$$

$$= \frac{1.0551 \times 10^3 \text{ J} \times 1.8}{3600 \times 9.290 \times 10^{-2} \text{ s.m}^2\text{.K}} = \frac{1899.181 \text{ J}}{334.44 \text{ s.m}^2\text{.K}}$$

$$= 5.6787 \text{ J/s} \cdot \text{m}^2 \cdot \text{K}$$

Since J/s = W, it can be included in the above expression to get units 5.6787 W/m^2·K. Therefore, the conversion factor = 5.6787.

200 Btu/h·ft^2·°F = 200 × 5.6787 W/m^2·K = 1135.74 W/m^2·K.

DIMENSIONS—ANALYSIS

Dimensional Formulae

A *dimensional formula* is a formula that explains the way in which fundamental units enter into the operation.

Dimensional formula expresses the quantity in secondary units. For example, the dimensional formula for acceleration is:

$$[a] = l \cdot t^{-2} \quad \text{...(6)}$$

$$= \text{length} \times \text{time}^{-2}$$

Equation (6) can be explained as follows. Acceleration is defined as velocity per unit time.

$$[a] = \frac{\text{velocity}}{\text{time}} \quad \text{...(7)}$$

Velocity is defined as a distance per unit time. Therefore, acceleration can be written as:

$$[a] = \frac{\text{Distance (length)}}{\text{time} \times \text{time}} = 1 \cdot t^{-2} \quad \text{...(8)}$$

The symbol [a] means the dimensional formula of the quantity of 'a'.

Applications : Dimensional formulae are used in order to convert the secondary units of one system into another. In these calculations, conversion factors are used cautiously. Then, the physical quantity is obtained in another system.

Dimensionless Equations

Dimensionless equation is defined as an equation, which consists of terms that have same dimensions.

The dimensionless equations are derived from basic laws mathematically, no matter however complicated they may be. An equation in which all terms have same dimensions is known as *dimensionally homogeneous equation*.

For example, consider equation for Reynolds number:

$$R_e = \frac{Du\rho}{\eta} \quad \text{...(9)}$$

where D = diameter of the pipe, m
u = velocity of flow, m/s
ρ = density of the fluid, kg/m^3
η = viscosity of the fluid, Pa·s

Consider the units in the numerator in equation (9)

$$Du\rho = \text{m} \times \frac{\text{m}}{\text{s}} \times \frac{\text{kg}}{\text{m}^3} = \frac{\text{kg}}{\text{s.m}}$$

Consider the units in the denominator in equation (9).

$$\eta = \text{Pa} \cdot \text{s} \quad \text{...(10)}$$

Since, Pa = kg/m·s^2, it can be substituted in equation (10)

$$\eta = \frac{\text{kg} \times \text{s}}{\text{m} \times \text{s}^2} = \frac{\text{kg}}{\text{m.s}}$$

Therefore, equation (9) may be written as:

$$R_e = \frac{\text{kg} \times \text{s}}{\text{m} \times \text{s}^2} = \text{dimensionless number}$$

Hence equation (9) is considered as dimensionless equation.

Consider another equation as a variation. For example, falling of a body in time, t, can be expressed as:

$$S = ut + (1/2)\, gt^2 \quad \text{...(11)}$$

where S = vertical distance, length
u = initial velocity, distance/time
t = time
g = acceleration due to gravity, distance/time^2

In equation (11), first and second terms are expressed separately as follows:

$$ut = \text{velocity} \times \text{time}$$

$$= \frac{\text{distance (length)}}{\text{time}} \times \text{time} = \text{distance (length)}$$

$$\frac{1}{2} gt^2 = \frac{\text{distance (length)}}{\text{time}^2} \times \text{time}^2 = \text{distance (length)}$$

Each term has the units of length. Equation (11) can be made dimensionless by dividing with 'S'.

$$1 = \frac{ut}{S} + \frac{1}{2} \cdot \frac{gt^2}{S} \qquad ...(12)$$

In equation (12), the dimensions get cancelled and each term is dimensionless.

The **advantages** of dimensionless equations are:

1. Unit of any system (cgs or fps or SI) can be used without introducing conversion factors. For example, length in either metres or feet can be substituted in equation (11).
2. Dimentionless equations are based on theoretical principles. They contain variables affecting the physical process.

Dimensional Equations

Dimensional equation is defined as an equation, which contains terms of varying *dimensions as it is obtained by empirical methods.*

Experimental results are correlated by empirical means. Therefore, dimensional consistency is ignored. Such equations are also known as *dimensionally non-homogeneous equations.*

For example, the rate of heat loss (by conduction and convection) from a horizontal pipe to the atmosphere may be written as:

$$\frac{q_c}{A} = 0.5 \frac{(\Delta t_s)}{(D_o')^{0.25}} \qquad ...(13)$$

where q_c = loss of heat, Btu/h
A = pipe surface, ft^2
Δt_s = excess of temperature of the pipe wall over that of atmosphere, °F
D_o' = diameter of the pipe, in

The quantities substituted for the terms must be expressed in the units mentioned above. For example, D_o' may be substituted only in inches, not in feet. The reasons are that the numerical coefficients such as 0.5, 1.25 and 0.25 are applicable for those units.

The **disadvantage** of this equation is that it has limited applications. It is particularly useful for calculations of a system under specified conditions.

Dimensional Analysis

Dimensional analysis is an important tool to convert the empirical relationships into theoretical principles on a rational basis.

In the pharmaceutical engineering, many physical problems have been solved completely by theoretical and mathematical methods. On the other hand, there are still many situations wherein empirical relationships have been established over a period of time, since theoretical relationships have failed to satisfy experimental results. Common examples related to these problems are - fluid flow, heat flow and mass transfer.

Dimensional analysis assumes that there must exist a relationship among all the factors affecting a process. This technique involves the following steps.

(1) All the factors are to be identified, which are important in the problem. Initial stages, empirical relationship may be adequate.
(2) These factors are grouped together into fewer numbers and expressed as dimensionless groups.
(3) Such groups are entered into final equation.
(4) Such equations are correlated to the possible physical laws.
(5) A possible mathematical solution is obtained.

In the above analysis, the first step is to consider the units for the verification of factors. For example, in the experiments on the fluid flow, the factors involved are listed below.

- pipe diameter (D), m — viscosity (η), Pa·s
- velocity (u), m/s — density (ρ), kg/m^3

These factors are varied as one at a time. Then the results are combined. It is shown by dimensional analysis that these factors must appear in a dimensionless group as shown below.

$$\frac{Du\rho}{\eta} \quad \text{or} \quad \text{m}\frac{\text{m}}{\text{s}} \cdot \frac{\text{kg}}{\text{m}^3} \cdot \frac{1}{\text{Pa.s}} = \frac{\text{kg}}{\text{s.m.Pa}} = \frac{\text{m.s}^2\text{.kg}}{\text{m.s}^2\text{.kg}}$$

This equation is expressed as Reynolds number, which has no dimensions. This example illustrates the success of the dimensional analysis. But heat transfer experiments on fluids involve about 11 factors. A total of five different expressions are obtained. Still dimensional analysis could provide a satisfactory equation to describe the heat transfer process.

Advantages:

(1) Dimensional analysis reduces drastically the number of independent variables that effect the problem.
(2) This analysis does not yield numerical values in the equation.
(3) This helps in constructing dimensionless (dimensionally homogeneous) equation.
(4) Very useful for any system of units (cgs or fps or SI).

Disadvantages : Dimensional analysis is a difficult process, if enough knowledge is not available about the physics of the situation.

Comment 1-8. When dimensionless equation is available for a particular process, conversion factor is not required. True or false. Explain.

Comment 1-9. Dimensional equations are not useful over dimensionless equation. True or false. Explain.

Summary

Pharmaceutical industrial processes are wide and varied and used in different areas of production: dosage forms, bulk drugs, antibiotics, biological, etc. The use of equipment and related aspects, and the unit operations and related considerations make the products effective and economical. Therefore, a broad understanding of the basic principles is essential. Every process involves several steps and each step is performed individually using a *unit operation*, e.g. size reduction, evaporation, filtration, etc. All industries employ a series of unit operations to produce products of commercial value. A *unit process* may be a chemical process or physical process. A few examples of unit processes are manufacture of common salt (a physical process) and production of paracetamol (chemical process).

Several scientific principles are applied to evaluate each unit operation and ultimately the unit process. The principles are: mass balance (law of conservation of mass) and energy balance (law of conservation of energy). Mass balance allows us to calculate percent recovery and validate the unit operation. Energy balance is the capacity to utilize the energy by balancing the energy; input energy = output energy. All the forms of energy are properly accounted. For example, for fluid flow, Bernoulli's theorem is applied and involves 5 forms of energies. Apart from these principles, several special laws such as ideal gas equation, Dalton's law of vapour pressures, etc. are also applied to describe the unit operation, e.g. distillation. While evaluating the parameters for balancing, the state (steady or unsteady) of the reaction needs to be specified. Further, the parameters are expressed in a proper system (mks). It is also necessary to translate data of other systems (cgs and fps) into mks system or vice versa. For this purpose, conversion factors are identified, which have to be used cautiously.

Dimensions (measurements) are included in the formulae, which explain the way in which fundamental units enter into the operation. If these formulae or equations are dimensionless, it is ideal, e.g. Reynolds number. This number remains the same, irrespective of the type of system (units) used. Dimensionless equations are based on theoretical principles. It is not always possible to obtain dimensionless equations. Dimensional equation can also be obtained to describe a unit operation (e.g. heat transfer), but such a system is applicable to a particular system (units), i.e. under

specified conditions. In the pharmaceutical engineering, many physical problems have been solved completely by theoretical and mathematical methods. Therefore, as a first line of investigation, dimensional analysis is attempted. It is an important tool to convert an empirical relationship into theoretical principles on a rational basis. Based on the analysis, a possible mathematical solution can be arrived. All reactions (physical/chemical) are balanced stoichiometrically, such that further calculations can be made quantitatively for obtaining the yield of products or consumption of reactants. Then only a reaction can be planned for obtaining the desired amount of product.

Glossary of Symbols

A = Pipe surface, ft^2.
D = Pipe diameter, m.
h = Viscosity, Pa·s.
F = Driving force.
g = Acceleration due to gravity, m/s^2.
R = Resistance.
R = Rankine.
r = Density, kg/m^3.
S = Vertical distance, m.
SI = Systeme Internationale.
u = Velocity, m/s.
t = Time, s.

QUESTION BANK

Each question carries one mark

Note : Encircle the alphabet which corresponds to the single best response.

1. Which one of the following is an example of a 'unit process'?
   A. Crystallisation B. Drying
   C. Filtration D. Production of penicillin
2. Which one of the following is an example of a 'unit operation'?
   A. Determination of viscosity B. Drying
   C. Production of tablets D. Synthesis of penicillin
3. Which one of the following is NOT a fundamental unit?
   A. Force B. Length
   C. Mass D. Time
4. Which one the following is NOT a derived unit?
   A. Energy B. Force
   C. Length D. Power

5. What is the conversion factor for length from FPS system to SI system?
   A. 0.03048 B. 0.3048
   C. 3.048 D. 30.48
6. If the fluid has the viscosity 0.20 poise, what is the corresponding value in SI system (Pa.s)?
   A. 0.002 B. 0.02
   C. 0.2 D. 2.0
7. If the density of calcium carbonate is 1.5 g/ml, what is its equivalent in SI system?
   A. 15.00 kg/cc B. 150.0 kg/cc
   C. 150.0 kg/m^3 D. 1500 kg/m^3
8. Reynolds number is an example for:
   A. dimensional equation B. dimensional formula
   C. dimensionless equation D. stoichiometric equation
9. Unit process is a sequence of operations involving one of the following.
   A. Chemical
   B. Chemical and physical
   C. Chemical, physical, and biological
   D. Physical
10. In a system, if the operating conditions are varying with time, such a system is known in one of the following terms.
    A. Dynamic state B. Equilibrium state
    C. Steady state D. Unsteady state

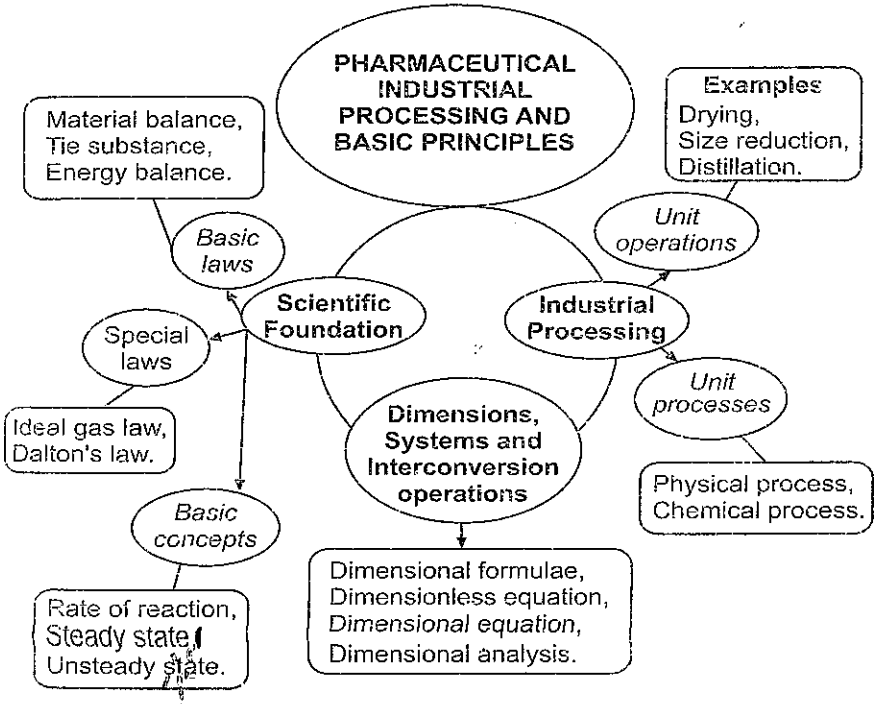
Each question carries 2 marks

1. Highlight the importance of unit operations in pharmaceutical engineering.
2. Describe the molecular concept of stoichiometry.
3. Give an expression to calculate the average molecular weight of a mixture.
4. How is the rate of a reaction expressed?
5. Distinguish between steady state and non-steady state.
6. Define the term 'dimensionless equation' with the help of an example.
7. Define dimensional equation. What are its limitations?
8. Define the term 'dimensionless equation'. What are its advantages?
9. Explain the concept of material balance for a physical process using a suitable example of a unit process.
10. Explain the term 'tie substance' along with its applications.

Each question carries 5 marks

1. Describe 'unit operation' and 'unit process'. Give two examples each.

2. Explain the term 'unit operation'. Describe the basic principles of various unit operations used in pharmaceutical and other associated industries.
3. Explain the term 'mass balance' and 'energy balance'. What are its applications?
4. Give an account of unit systems and their inter-conversions.



MIND MAP OF PHARMACEUTICAL INDUSTRIAL PROCESSING AND BASIC PRINCIPLES

CHAPTER 2

Flow of Fluids

Fluid Statics
Fluid Dynamics
Bernoulli's Theorem
Energy Losses
Measurement of Rate of Flow of Fluids

LEARNING OBJECTIVES

After reading this chapter, the reader should be able to:

- Appreciate the importance of fluid flow and parameters relevant to the study.
- Describe different types of manometers and pressure gauges to evaluate the pressure at any point, as per the principles of fluid statics.
- Explain the Reynolds experiment for understanding the fluid dynamics.
- Describe the proposal of the Bernoulli's theorem, its applications for energy balancing and for evaluating the energy losses.
- Measure the rate of flow of liquids using different methods giving importance to the principles, construction and applications.

Fluid flow may be defined as the flow of substances that do not permanently resist distortion.

This definition covers the flow of liquids and gases. At a given temperature and pressure, a fluid possesses a define density. In case of liquids, the density is not appreciably affected by moderate changes in pressure. In case of gases, density is affected appreciably by both temperature and pressure. A fluid is said to be incompressible, if a fluid is inappreciably affected by changes in pressure, but gases can be compressed. Most of the liquids are incompressible.

The term '*fluid*' covers liquids and those gases in which the effects due to compressibility may be neglected.

Fluid is considered to be a mass of a substance formed by a series of layers. When an attempt is made to change its shape, the layers of fluid slide over one another, until a new shape is attained. At the end, the fluid is relieved off the stresses that it encountered during the flow.

Fluid (liquid or gas) is a form of matter that cannot achieve equilibrium under an applied shear stress, but deforms continuously or flow as long as shear stress is applied.

Flow of fluids is observed while handling materials.

(a) **Handling of liquids :** Transportation of materials such as solvents, solutions and suspensions is simpler, cheaper and less troublesome than handling of solids in industrial operations.

(b) **Handling of solids :** Solids are handled in a finely divided state in the form of suspension of fluids, so that transportation becomes easy. This two-phase mixture is known as '*fluidised solids*'.

During the handling process, the behaviour of liquids changes transiently. Such changes have profound influence on heat transfer process, energy losses during pumping, energy changes in pumping, etc. Therefore, fluid flow is treated independently.

Flow of fluids is involved in a number of areas of pharmaceutical industries. Some of them are:

- Passing of reactants (liquids or gases) into the reaction system.
- Transferring of air, nutrient broth into the fermenter.
- Bottling of liquid medicaments into suitable containers.
- Transporting of sterile air and sterile water in the production of parenterals.
- Mixing of solids and liquids in case of suspensions.
- Packing of semisolids in containers.

The nature of flow influences the type of equipment used for handling, i.e. valve, pump, pump capacity, diameter of pipe, etc. Flow characteristics through pipes and channels are relevant. At the same time, the measurement of rate of flow is necessary for the quantification of additives (reactants) into a process.

Fluid flow is emerged as a special branch.

Fluid mechanics is that branch of science, which deals with the behavior of fluids at rest as well as in motion.

Fluid mechanics is divided into fluid statics and fluid dynamics.

- *Fluid statics* deals with fluids at rest in equilibrium.
- *Fluid dynamics* deals with fluids in motion.

When the fluid is water, it is termed as hydrostatics.

Comment 2-1. What are the differences between gases and fluids?

FLUID STATICS

Fluid statics deals with the fluids at rest in equilibrium.

The behaviour of a liquid at rest, the nature of pressure it exerts and the variations of pressure at different layers in the liquid are some of the relevant aspects in the pharmaceutical engineering.

The study of fluids at rest is based on two principles.

1. Pressure at a point is the same in all directions.
2. Pressure is the same at all points in a given horizontal line in a continuous fluid.

Pressure Difference Between Layers of Liquid

Pressure (or intensity of pressure) may be defined as the force exerted on a unit area. Pressure may be expressed as absolute pressure (i.e. with reference to the vacuum or absolute zero pressure). It may be expressed with reference to the atmospheric pressure (at sea level, 760 mmHg or 1.013 × 105 Pa), using manometer. Consider a column of liquid as shown in Figure 2-1(a). Two openings are provided to the wall of the vessel at different heights. The rates of flow from these openings are different (Figure 2-1a). This is due to the differences in the pressures exerted at different heights. This behaviour can be quantitatively expressed as follows.

Consider a stationary column of fluid as shown in Figure 2-1(b). The pressure P_s pascals is acting on the surface of the fluid. The stationary column is maintained at constant pressure by applying pressure, P pascals at point A.

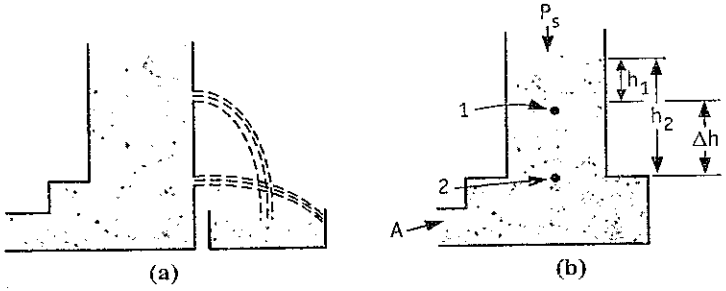


Figure 2-1. Hydrostatic pressure observed at different layers of a stationary column.

Let the cross-section of the column be S metre square and is uniform from top to bottom. The force (further pressure) acting on the liquid at different levels of the liquid column can be determined. The forces (newton) acting on each side (horizontal components) of the point 1 are mutually nullified. The forces in newtons acting below and above the point 1 are evaluated.

Force acting on the liquid at point 1 = force on the surface + force exerted by the liquid above the point 1 ...(1)

Substituting the force with pressure × area of cross section (S) in equation (1) gives:

Pressure at point 1 × surface area = (Pressure on the surface × surface area) + (mass × acceleration) ...(2)

$P_1S = P_sS +$ (volume × density × acceleration due to gravity)

$= P_sS +$ (height × area × density × acceleration due to gravity)

$P_1S = P_sS + h_1S\rho g$ ...(3)

Since cross sectional surface area is same, equation (3) may be written as:

$$P_1 = P_s + h_1\rho g \quad ...(4)$$

Similarly, the pressure acting on the liquid at point 2 may be writtenas:

$$P_2 = P_s + h_2\rho g \quad ...(5)$$

The difference in the pressure may be obtained by subtracting equation (4) from equation (5) as:

$$P_2 - P_1 = P_s + h_2\rho g - P_s - h_1\rho g$$

$$\Delta P = h_2\rho g - h_1\rho g$$

$$\Delta P = (h_2 - h_1)\,\rho g$$

$$= \Delta h\rho g \quad ...(6)$$

Therefore, the pressure difference (ΔP pascals) between any two points can be measured by the distance between those points in a fluid. If the density of fluid (ρ kilogram per metre cube) varies with variation of pressure, an average density could be used. The variation in densities is quite negligible for liquids and gases. Since the difference in the heights (Δh metre) is necessary for the measurement, height can be measured from the bottom of the stationary column.

Pressure difference ∝ height difference

Therefore, pressure is expressed in terms of height (in units) and often referred as head.

Applications : The principle of fluid statics is employed in the working of manometers. In such cases, the pressure difference (ΔP) is measured in terms of difference in the heights of the liquid column. It is also applied for quantification of fluid flow as in Bernoulli's theorem.

Manometers

Manometers are the devices used for measuring the pressure difference.

Pressure differences based on the principle of balancing the column of liquid by the same or another column of liquids. Three different manometers are available. These are:

1. Simple 2. Differential 3. Inclined

The principles and applications of these manometers are discussed in the following sections.

Simple manometer : *Simple manometer* is a device which measures pressure at a point in a fluid contained in a pipe or vessel.

This manometer is the most commonly used. The construction of a simple manometer is shown in Figure 2-2. It consists of a glass U tube filled with a liquid (A) of density, ρ_A, kilogram per metre cube. Above liquid A, the arms are filled with liquid B of density ρ_B kilogram per metre cube. The liquids A and B are immiscible and the interface can be seen clearly.

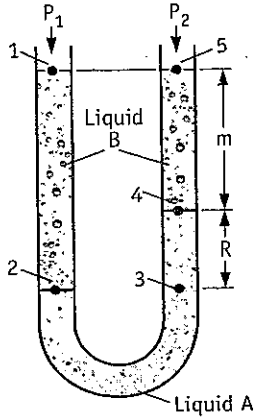


Figure 2-2
Simple manometer.

If two different pressures are applied on the two arms, the meniscus of liquid A will be higher in one arm than the other (Figure 2-2). Let the pressure at point 1 is P_1 pascals in left hand-side of the limb. Let the pressure at point 5 is P_2 pascals in the right hand-side of the limb. From the principles of fluid statics, the pressure at point 2 can be written as:

$$\text{Pressure at point 2} = P_1 + (m + R)\,\rho_B g \qquad ...(7)$$

where $(m + R)$ = distance from points 3 to 4 + distance from points 4 to 5.

Since, points 2 and 3 are at the same level, the pressure at point 3 may be written as:

$$\text{Pressure at point 3} = P_1 + (m + R)\,\rho_B g \qquad ...(8)$$

The pressure at point 4 can be written from the right hand-side of the limb (from P_2) as:

$$\text{Pressure at point 4} = P_2 + gm\rho_B \qquad ...(9)$$

In another manner, the pressure at point 4 can be written from point 3 (i.e. from left hand-side) as:

$$\text{Pressure at point 4} = P_1 + \rho_B\,(m + R)\,g - \rho_A\,Rg \qquad ...(10)$$

Equations (9) and (10) represent the pressure at point 4 only. Hence, these equations should be equal. This relationship may be written as:

$$P_1 + g\,\rho_B\,(m + R) - \rho_A\,Rg = P_2 + gm\rho_B$$

$$P_1 - P_2 = gm\rho_B - \rho_B\,(m + R)\,g + \rho_A\,Rg$$

$$\Delta P = m\rho_B g - m\rho_B g - R\rho_B g + R\rho_A g$$

$$\Delta P = R\,(\rho_A - \rho_B)\,g \qquad ...(11)$$

The important conclusions drawn from equation (11) are:

(1) It is easy to measure R value (metres), i.e. the difference in the levels of liquid A in the two limbs.

(2) The value ΔP pascals is independent of the value of m and also the dimensions of the U tube.

When wide ranges of pressure are applied, the sensitivity of liquids employed in the measurement is important. If the pressure differences are large, mercury (high density, liquid A) can be used as manometric liquid. Mercury has a very low vapor pressure and hence, it is an excellent fluid to be used in a barometer. Liquids such as benzene have high vapor pressure and hence volatile. Mercury is non-corrosive and does not react with the fluid whose pressure is to be measured. It can be quickly adjusted with pressure changes, owning to its low viscosity. Mercury manometers are employed for measurements of pressure in the range of 0.5 to 17 cm using U tube design. Normally the 'U' tube is mounted in a wooden stand. A graduated scale (in mm, millimeters) is fixed in order to measure the height (distance), the levels of mercury in the two arms. The height directly gives the pressure. If the pressure differences are small, liquids such as alcohol, water (for gases) and carbon tetrachloride are used.

Applications : (1) Simple manometer helps in measuring the consumption of gases in the chemical reactions. (2) Manometers are used in conjunction with flow meters for the measurement of flow of fluids. For example, venturi meter and orifice meter are used for the measurement of pressure head using a manometer. Pitot tube measures the velocity head using a manometer.

Differential manometers : *Differential manometer* is a manometer which measures the difference of pressures between any two points in a pipe or vessel containing fluid.

Differential manometers find occasional applications. This manometer is suitable for measurement of small pressure differences. It is a sensitive device and useful for measuring even small gas pressures (heads).

The construction of a differential manometer is given in Figure 2-3. The differential manometer is also known as *two-fluid U-tube manometer*. It contains two immiscible liquids A and B having nearly same densities. The U tube consists of enlarged chambers on both limbs. Hence, the me-

niscus of the liquid in these enlarged chambers does not change appreciably with changes in the reading R.

Using the principle of simple manometers, the pressure difference (ΔP pascals) can be written as:

$$\Delta P = P_1 - P_2 = R\,(\rho_C - \rho_A)\,g \qquad ...(12)$$

Equation (12) indicates that the smaller the difference $(\rho_C - \rho_A)$, the larger will be reading on the manometer (R metres) for a given value of ΔP.

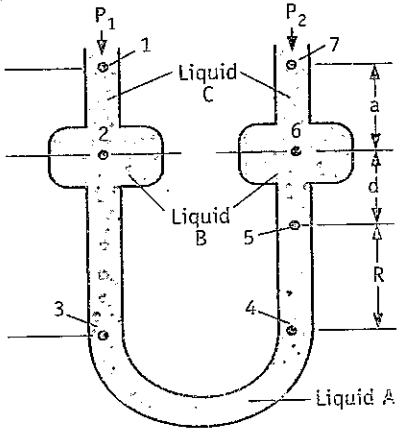


Figure 2-3. Differential manometer.

Applications : Micromanometers based on the liquid column principle are available commercially. They measure the reading with extreme precision and sensitivity. These are free from errors due to capillarity and require no calibration, apart from checking the micrometer scale.

Inclined manometer : *Inclined manometer* is a manometer which measures the minute pressure differences between any two points in a fluid contained in a pipe or vessel.

Inclined manometer is a modification of differential manometer. This type of manometer increases the accuracy of the pressure determination particularly for small head. The construction of a inclined manometer is given in Figure 2-4. In this type, the vertical leg is enlarged so that the movement of meniscus in this enlargement is negligible within the range of gauze. But, leg containing one meniscus is inclined in such a manner that for a small value of reading, 'R' meniscus moves a considerable distance along the tube. This distance is equal to 'R' (vertical) divided by the sine of the angle of inclination α (sin α). By making 'α' small, the value of inclined reading (R_1) is increased.

The principles of manometers also apply to fluids in motion. The presence of the meter should minimize perturbation in flow.

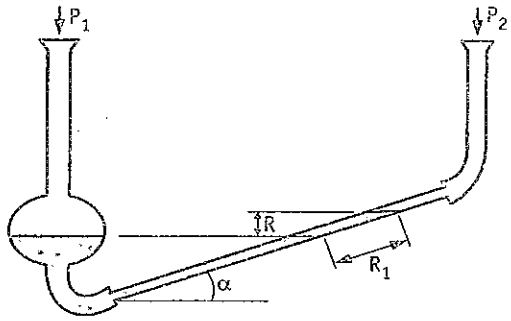


Figure 2-4. Inclined manometer.

Mercury Pressure Gauges

Normally, mercury 'U' tube is mounted in a wooden stand. A graduated scale (in millimeters) is fixed in order to measure the height (distance), the levels of mercury in the two arms. The height directly gives the pressure.

Vacustat : It is a useful pressure gauge, which is employed in conjunction with an oil pump. *Macleod gauge* is widely found in research laboratories. This gauge requires very large quantity of mercury. It is expensive, but the apparatus may break during usage or storage. There would be considerable toxic hazard.

Pirani or Penning gauze : This gauge is recommended for high vacuum applications. This gauge operates on the following principle. When gas molecules in the region of a detector are struck by electrons from the heated element (the ion source), molecules become electrically charged. Hence, these get attracted towards the detector site, where these cause an electric circuit. The current is amplified and calibrated to indicate the pressure, which is displayed on a meter (scale) or by means a digital readout. This gauge may be inserted directly into the vacuum line.

There are a few special type of mercury gauges (examples is monostat), which not only indicate the pressure, but also maintain a constant pressure.

Mechanical Pressure Gauges

Mechanical pressure gauges are the mechanical elements used for measuring the pressure.

In the mechanical devices, a body or elastic element deflects under action of the applied pressure. Whenever, there is a change in pressure, the mechanical elements may bend, deform or deflect. Such elements are termed as *transducers*. These can take one form of energy from measuring source (air compressed from a cylinder) and supply energy of a different kind (mechanical power), thereby the pressure differences is indicated.

The elastic deflection is mechanically magnified and operates a pointer moving against a graduated circumferential scale. This principle is illustrated using an example, C-shaped Bourdon gauge (Figure 2-5).

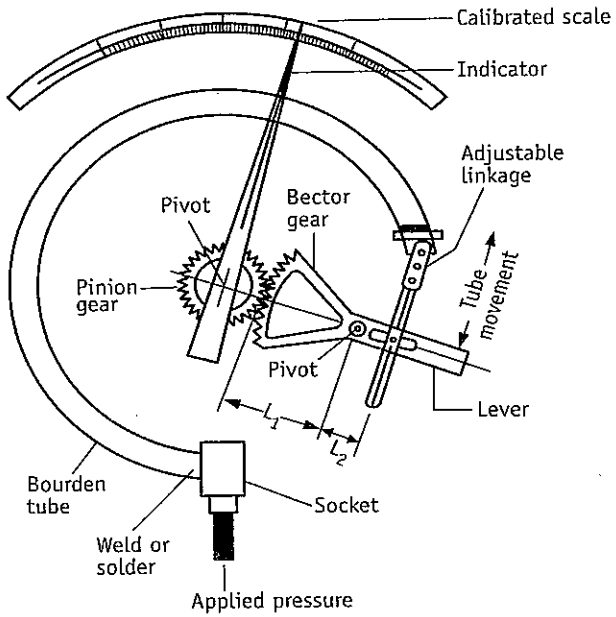


Figure 2-5. Bourdon pressure gauge.

C-Shaped Bourdon gauge : It consists of a length of thin walled metal (bronze, phosphor bronze, stainless steel and nickel alloys) tubing (Figure 2-5). This tube is flattened to approximately an elliptical cross-section and then rolled into a C shape. The arc of the gauge is in between 180 to 270°. The tube has a pressure inlet at one end and other is free end sealed. This is called as the tip.

Under pressure, the elliptical section tends to change its shape to a circular form. The deflection of the tip depends on the radius of the bend, total length of the tube, Young's modulus and elasticity of the tube material. Bourdon gauge has good sensitivity and repeatability. It is useful in the range of 10^6 to 10^8 Pa.

Diaphragm pressure gauge : This gauge consists of an elastic steel corrugated diaphragm, which is sensitive to pressure changes (Figure 2-6). Under pressure, the diaphragm gets deformed elastically, which is transmitted to a pointer (indicator) by a similar arrangement as in the case of Bourdon pressure gauge. However, this gauge is used to measure relatively low pressure intensities.

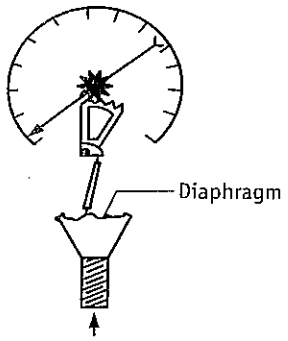


Figure 2-6
Diaphragm pressure gauge.

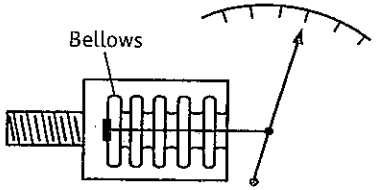


Figure 2-7
Bellows pressure gauge.

Bellow pressure gauge : This gauge consists of metallic tube having deep circumferential corrugations, which is sensitive to pressure changes (Figure 2-7). Due to pressure changes, the bellow expands or contracts, thereby the pointer moves on a graduated circular dial.

Comment 2-2. Why is fluid pressure difference termed as head and reported in meters (height)?

Comment 2-3. Why is mercury used as a preferred liquid in the manometer?

FLUID DYNAMICS

Fluid dynamics deals with the study of fluids in motion.

Study of flow properties of liquids is important for pharmacists working in the manufacture of dosage forms, such as simple liquids, gels, ointments, creams and pastes. These systems change their flow behaviour, when exposed to different stress conditions in the following situations.

(1) **Manufacture of dosage forms :** Materials undergo processes such as mixing, flowing through pipes and getting filled in the containers. Flow related changes influence the selection of mixing equipment.

(2) **Handling of drugs for administration :** The syringeability of the medicines, pouring of the liquids, extrusion of ointment from tubes etc. depend on the changes in flow behaviour of dosage forms.

Thus, flow behaviour of liquids is of relevance in pharmacy. Performance of a product depends on the net effect of all the above mentioned processes. Therefore, flow properties are used as important quality control tools to maintain the superiority of the product and to reduce the batch to batch variations.

In general, engineering of fluid flow considers the macroscopic properties. The molecular level interactions are beyond the scope of this book (Refer the book *Physical Pharmaceutics-II* by C.V.S. Subrahmanyam, Vallabh Prakashan).

Nature of Fluid Flow—Reynolds Experiment

The flow of fluid through a closed channel (pipeline) can be either viscous or turbulent. These can be observed in the classical Reynolds experiment. The assembly of the apparatus for the Reynolds experiment is shown in Figure 2-8.

A glass tube is connected to a reservoir of water as shown in Figure 2-8. The rate of flow of water through the tube can be increased or decreased at will through a valve. A reservoir of coloured solution is connected to one end of the glass tube with the help of nozzle(s). Therefore, coloured solution can be introduced into the glass tube as a fine stream. From this experimental setup, the following observations may be made and conclusions can be drawn.

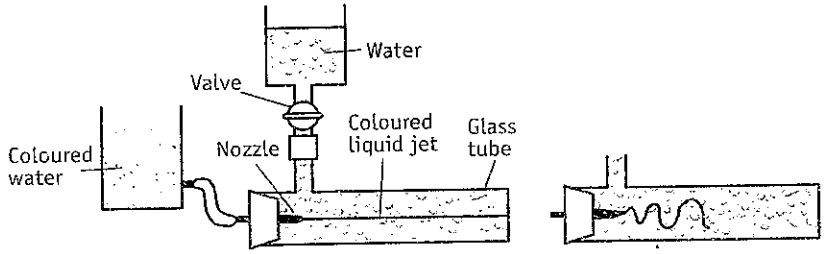


Figure 2-8. The assembly of the apparatus of the Reynolds experiment.

(a) *Laminar Flow* : When the velocity of water is low, the thread of coloured water maintains its identity throughout the tube. By introducing similar jets of coloured water at different points in the cross section of the glass tube, it can be noted that no part of the tube exhibits the signs of mixing. In other words, the colour streams are seen as parallel lines. The flow of water is considered to be *viscous* or *streamline* or *laminar*.

A *laminar flow* is one in which the fluid particles move in layers or laminar with one layer sliding over the other. Therefore, there is no exchange of fluid particles from one layer to the other. Hence, transfer of lateral momentum to the adjacent layers is not observed.

(b) *Turbulent flow* : When the velocity of water is increased (by increasing the pressure difference, ΔP), the threads of coloured water disappear and the entire mass of water gets uniformly coloured. It indicates complete mixing of solution. Then, the flow of water is considered to be *turbulent*.

When the flow attains a certain velocity, it no longer remains steady and vortices or eddy currents appear. In turbulent flow, the order is lost and motion is irregular. All the fluid particles are disturbed and get mixed up with each other. Thus, there is a continuous transfer of momentum to adjacent layers. Such a large shear stress must be overcome. In this process, the mechanical energy is lost (degraded) and dissipated as heat. Such a diffused flow is called *turbulent flow*.

The loss of energy is much smaller in laminar flow. The turbulent mechanisms carry motion, heat or matter from one part of the fluid to another part. These are absent in laminar flow. The transfer of shear stress arising in the variations in velocities is responsible for viscosity. Heat by conduction and matter by diffusion are less important in turbulent flow.

(c) *Critical behaviour* : The change over of the flow from viscous to turbulent is a critical factor.

Critical velocity is defined as average velocity of any fluid at which viscous flow changes into turbulent flow.

Once critical velocity is crossed, the shear stress is so great that streamline flow breaks down. The liquid is also given a random radial velocity and mixing occurs due to formation of eddies.

Reynolds number : In Reynolds experiment, the flow conditions are affected by four factors.

Diameter of pipe, m (D)
Average velocity, m/s (u)
Density of liquid, kg/m^3 (ρ)
Viscosity of the liquid, Pa·s (η)

These factors are grouped into an expression as given below.

$$\text{Reynolds number, } R_e = \frac{Du\rho}{\eta} \qquad ...(13)$$

Reynolds number is obtained by the following equation.

$$\text{Reynolds number, } R_e = \frac{\text{inertial forces}}{\text{viscous forces}}$$

$$= \frac{\text{mass} \times \text{acceleration of liquid flowing}}{\text{shear stress} \times \text{area}}$$

The Reynolds number describes the ratio of the inertia and viscous (or friction forces).

- The higher the Reynolds number, greater is the relative contribution of inertial effects.

- At very low R_e, viscous effects predominate and the contribution of inertial forces can be ignored.

Inertial forces are due to the mass and the velocity of the fluid particles trying to diffuse the fluid particles. The viscous force is the frictional force due to the viscosity of fluid, which makes the motion of fluid in parallel layers.

Therefore, at low velocities, the inertial forces are less when compared to the frictional forces caused by the viscosity. The resulting flow will be viscous in nature, i.e. the particles move in parallel layers. For this reason, laminar flow is sometimes known as *viscous*. On the other hand, when inertial forces are predominant, the fluid layers break up due to the increase in velocity, hence, turbulent flow takes place.

It is a dimensionless group, because the units of factors mutually get cancelled. If $R_e < 2100$, the flow is said to be laminar and if $R_e > 4000$, the flow is said to be turbulent. If R_e lies between 2100 to 4000, the flow changes from laminar to turbulent. The region 2100 to 4000 is known as critical region. For design purposes, the safety practice assumes that the turbulent flow exists at all Reynolds numbers greater than 2100.

Applications : (1) Reynolds number is used to predict the nature of flow (viscous or turbulent) in a particular set of experimental conditions. (2) The physical stability of suspensions (or emulsions) depends on the rate of settling of particles (or globules). For the study of sedimentation of particles, Stokes' law is used. In this study, rate of sedimentation of particles must not be too rapid to create turbulence. Therefore, type of flow (whether laminar or turbulent) is important. Accordingly Stokes' equation is modified to include Reynolds number. (3) The rate of heat transfer in liquids also depends on the flow, whether viscous or turbulent.

Variation in the Velocity of Flow Across the Cross-Section : When the local velocity of the fluid is plotted against distance from the wall (Figure 2-9), the following conclusions can be drawn.

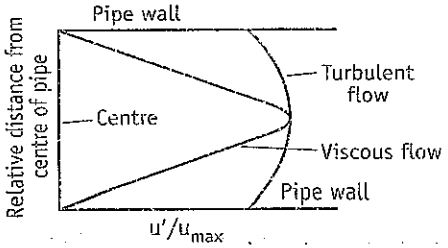


Figure 2-9. Distribution of fluid velocities across the cross section of a pipe.

- The flow of fluid in the middle of the pipe is faster than the fluid nearer to the wall.

- The velocity of fluid approaches zero as the pipe-wall is approached.
- At the actual surface of the pipe-wall, the velocity of the fluid is zero.

Since variations are observed in velocity of flow across the cross section, there should be some means of estimating average velocity.

- In viscous conditions, the average velocity over the whole cross section is 0.5 times the maximum.
- In turbulent flow, the average velocity over the whole cross section is 0.8 times the maximum.
- Since the velocity of the fluid is zero at the wall surface, there should be some layers in viscous flow near the pipe-wall, which acts as a stagnant layer.
- A gradual transition from one region to another, there exists a *boundary layer* which is known as buffer layer. This buffer layer oscillates between viscous flow and turbulent flow.
- Even if the flow is turbulent at the centre (of the pipe) and viscous at the surface of the wall, a buffer layer exists.

It must be emphasized that boundary layer can never be eliminated. Increasing the velocity of the fluid over the surface will reduce the thickness of the layer, but it will be never eliminated entirely.

Applications : (1) Though the general principles are mentioned above, considerable variation in velocity distribution may be possible with changes in roughness, direction, temperature or cross section of the pipe. Due to these reasons, the shape of curves may be changed.

(2) The nature of flow of liquids in pipes determines the rate of heat transfer. The buffer layer in turbulent flow and stagnant layer in viscous flow offer resistance to heat transfer. Further discussion on rate of heat transfer is dealt in Chapter 5 'Flow of Heat'.

Comment 2-4. The flow of fluid in the middle of the pipe is faster than the fluid present near to the wall. Why?

Comment 2-5. State the relationship between Reynolds number and fluid flow.

BERNOULLI'S THEOREM

A fluid in motion is subjected to several forces, which result in the variation of the acceleration and the energies in the flow phenomenon. When the principle of conservation of energy is applied to the flow of fluids, the resulting equation is called Bernoulli's theorem.

Pumps generally supply energy for conveying liquids from one point to another. Consider such a pump working under isothermal conditions between points A and B, as shown in Figure 2-10.

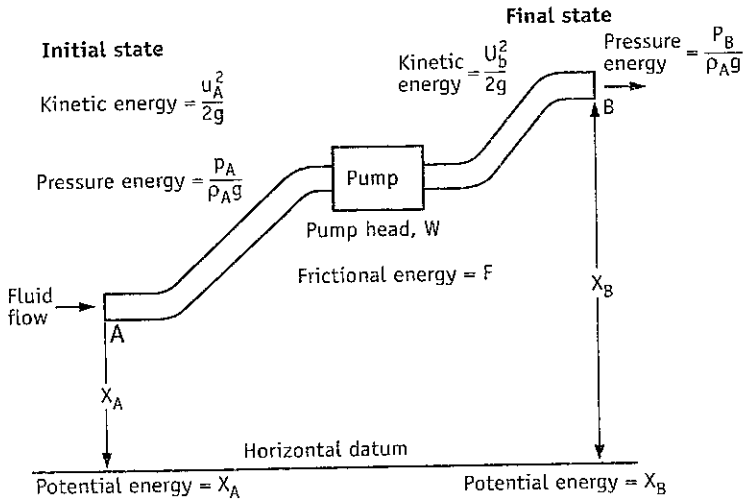


Figure 2-10. Development of Bernoulli's theorem.

Bernoulli's theorem states that in a steady state ideal flow of an incompressible fluid, the total energy per unit mass, which consists of pressure energy, kinetic energy and datum energy, at any point of the fluid is constant.

At point A, one kilogram (unit mass) of liquid is assumed to be entering. At this point, liquid experiences mechanical energy, which can be expressed as pressure energy, kinetic energy and potential energy, which are obtained as follows.

Pressure energy or flow energy is an energy form peculiar to the flow of fluid. The work done is the product of pressure energy and the volume. The volume of a unit mass of the liquid is reciprocal of the density, ρ. For an incompressible fluid, the density is not dependent on the pressure, so for unit mass of fluid, the pressure energy is P/ρ. Since liquid is flowing through the pipe at certain pressure, pressure energy in joules may be written as:

$$\text{Pressure energy} = \frac{P_A}{g\rho_A} \qquad ...(14)$$

where P_A = pressure at point A, Pa
g = acceleration due to gravity, m/s
ρ_A = density of the liquid, kg/m^3

Potential energy (datum energy) of a body is defined as the energy possessed by the body by virtue of its position or configuration. Potential energy of a body is its capacity to do work by reason of its position relative to some centre of attraction. The point A is considered at a height of X_A

metres above the horizontal datum plane. The potential energy for one kilogram of liquid may be written as:

$$\text{Potential energy} = X_A \qquad ...(15)$$

Kinetic energy of a body is defined as the energy possessed by the body by virtue of its motion. Since liquid is under motion, the velocity of liquid may be designated as u_A metre per second at point A. The kinetic energy may be expressed as:

$$\text{Kinetic energy} = \frac{u_A^2}{2g} \qquad ...(16)$$

The total energy at point A may be summarised by combining equations (14), (15) and (16) as:

Total energy = pressure energy + potential energy + kinetic energy

$$\text{Total mechanical energy at point A} = \frac{P_A}{g\rho_A} + X_A + \frac{u_A^2}{2g} \qquad ...(17)$$

According to Bernoulli's theorem the total energy at point A is constant. Therefore, equation (17) is:

$$\text{Total energy at point A} = \frac{P_A}{g\rho_A} + X_A + \frac{u_A^2}{2g} = \text{constant} \qquad ...(18)$$

After the system reaches the steady state, whenever one kilogram of liquid enters at point A, another kilogram of liquid leaves at point B. Therefore, energy content of one kilogram liquid that is being displaced at point B may be written (Bernoulli's theorem) as:

$$\text{Total energy at point B} = \frac{P_B}{g\rho_B} + X_B + \frac{u_B^2}{2g} = \text{constant} \qquad ...(19)$$

where X_B = height from the datum to the pipe, m
u_B = velocity at point B, m/s
P_B = pressure at point B, Pa
ρ_B = density at point B, kg/m^3

If there is no gain or loss of energy, the principle of conservation of energy may be applied to the two points A and B.

INPUT = OUT PUT

Total energy at point A = Total energy at point B

$$\frac{P_A}{g\rho_B} + X_A + \frac{u_A^2}{2g} = \frac{P_B}{g\rho_B} + X_B + \frac{u_B^2}{2g} \qquad ...(20)$$

Theoretically all kinds of energies involved in fluid flow should be accounted. In the transportation of fluid, the pump has added certain amount of energy, which can be written as:

$$\text{Energy added by the pump} = +w \text{ J} \qquad ...(21)$$

During the transportation of liquid, some energy is converted to heat due to frictional forces and it is inevitable. The energy loss may be written as:

$$\text{Loss of energy due to friction in the line} = -F \text{ J} \qquad ...(22)$$

The energy balance between points A and B can be accounted by including equations (21) and (22) in equation (20). This complete equation representing such energy may be written as:

$$\frac{P_A}{g\rho_A} + X_A + \frac{u_A^2}{2g} - F + w = \frac{P_B}{g\rho_B} + X_B + \frac{u_B^2}{2g} \qquad ...(23)$$

Equation (23) is called *Bernoulli's equation*. Bernoulli's theorem, although derived over two ends of a system, it is applicable between any two points in a system. Equation (23) is numerically correct. But it is not correct theoretically, since each of the terms in equation (23) is actually energy term and should be measured in the units of joules per unit mass. In practice, these terms are always referred as the heights and often measured in terms of height of a column of liquid.

Power required for the fluid to flow at a certain rate may be calculated using equation (23), i.e. driving of the liquid. The total head against which a pump must work is:

$$\text{power required} = \frac{w}{g} + \sum H$$

where $\sum H$ = sum of heads, m; w = work done, J

If the work (w) is performed and energy acquired by a unit mass of liquid is ΣHg, then power required to transfer mass, m in time t is given by:

$$\text{Power} = \frac{\sum Hgm}{t}$$

As the volume flowing in unit time (Q) is $m/\rho t$, the power term is given by:

$$\text{Power} = Q\sum Hg\rho$$

Applications:

(1) Bernoulli's theorem is applied in the measurement of the rate of fluid flow using orifice meter and venturi meter.

(2) Bernoulli's theorem is applied in the working of centrifugal pumps. In these pumps, the kinetic energy is converted into pressure head, which helps in pumping the liquids.

(3) It is easy to measure heights and apply them as energy terms, which is a contribution of Bernoulli's theorem.

Concept of Head (Pressure Head)

The terms in Bernoulli's equation represent energy and supposed to have the units of energy. But numerically these terms give the units of metre. Therefore, energy terms can be measured in the units of metre, which is a unit of height. Hence these terms are known as *heads*.

The *pressure head* is defined as the height of a column of liquid of known density, which is numerically equal to pressure energy term.

The units of height can be obtained by considering the pressure energy term, i.e. equation (14).

$$\text{Pressure energy} = \frac{P_A}{g\rho_A} = \frac{\text{pressure}}{\text{acceleration due to gravity} \times \text{density}}$$

Consider the units for equation (14).

$$\text{Pressure energy} = \frac{\text{N}}{\text{m}^2} \cdot \frac{1}{(\text{m/s}^2)} \cdot \frac{1}{(\text{kg/m}^3)}$$

$$= \frac{\text{N} \times \text{s}^2 \times \text{m}^3}{\text{m}^2 \times \text{m} \times \text{kg}} = \frac{\text{N.s}^2}{\text{kg}} \qquad ...(24)$$

But N (newton) = kg·m/s^2. Substituting this term in equation (24) gives:

$$\text{Pressure energy} = \frac{\text{kg} \times \text{m} \times \text{s}^2}{\text{s}^2 \times \text{kg}} = \text{m}.$$

Thus, pressure energy is in metre, i.e. as a height. Therefore, the height is termed as head in the discussion of hydraulics. Hence, pressure energy is called pressure head.

In an analogous manner, there are different heads in the Bernoulli's equation (18), namely:

potential head (X) or datum head

velocity head ($u^2/2g$) or kinetic head

pressure head (P/gr) or static head

Similarly, F is known as friction head and W is the head that is added by the pump. In the same manner, the sum of the pressure head, the velocity head and the potential head is known as total head or total energy per unit weight of the fluid.

ENERGY LOSSES

Bernoulli's equation includes the term 'loss of energy' in the pipe. According to law of conservation of energy, energy balances have to be properly accounted. Therefore, it is necessary to calculate the energy losses. Fluids experience energy losses in several ways while flowing through a pipe. Some of them are:

1. Friction losses
2. Losses in fittings
3. Enlargement losses
4. Contraction losses

These are discussed in the following sections.

Friction Losses

During the flow of fluids, frictional forces cause a loss in pressure (ΔP_f pascals). The fluid flow can be either viscous or turbulent, which also influences the losses. In general, the pressure drop (ΔP_f) due to friction in a fluid is:

- directly proportional to the velocity of the fluid (u), m/s
- directly proportional to the density of the fluid (ρ), kg/m^3
- directly proportional to the length of the pipe (L), m
- inversely proportional to the diameter of the pipe (D), m

These relationships are proposed in *Fanning equation* for calculating the friction losses, irrespective of the nature of flow (viscous or turbulent).

$$\text{Fanning equation (viscous or turbulent):}\quad \Delta P_f = \frac{2 f_u^2 L\rho}{D} \qquad ...(25)$$

where f = friction factor ; ΔP_f = pressure drop, Pa

Equation (25) considers the friction losses when the fluid is passing through a straight pipe. The value of f depends on:

- Nature of flow of the fluid (turbulent or viscous).
- Roughness of the inner surface of the pipe. The roughness factors for some conditions of pipes are given below.

Condition of pipe	*Roughness factor*
Smooth brass, copper or lead pipe	0.6
New steel or cast-iron pipe	1.0
Old steel pipe	1.6
Badly rusted cast-iron pipe	2.5

The numerical values reported in the above table give a rough estimate of the magnitude of the effect, which contributes to the friction factors. Frictional loss can be reduced by the addition of soluble, high molecular weight polymers in low concentrations.

In practice, fluids are rarely handled in viscous flow. For viscous flow, *Hagen-Poiseuille equation* could be employed for calculating the pressure drop due to friction.

$$\text{Hagen-Poiseuille equation (viscous flow):}\quad \Delta P = \frac{32\, Ln\eta}{D^2} \qquad ...(26)$$

where η = viscosity of the liquid, Pa·s
ΔP_f = pressure drop, Pa

If the viscosity (η) is known, Hagen-Poiseuille's equation permits the calculation of pressure drop due to friction. However, equation (26) is normally used to calculate the viscosity, by experimentally estimating ΔP. Friction losses are permanent, since potential and kinetic energies are converted into heat.

Losses in Fittings

Normally, a large number of fittings are included in a pipeline (Figure 2-11). For a liquid passing through a straight pipe, Fanning equation is applicable for the losses. When fittings are introduced into a straight pipe, they cause disturbances in the flow, which results in additional loss of energy. It is difficult to specify the loss due to each type, because of varying types of fittings.

Losses in fittings may be due to

- change in direction, e.g. elbow fittings,
- change in the types of fittings, e.g., coupling, union, valve or meter.

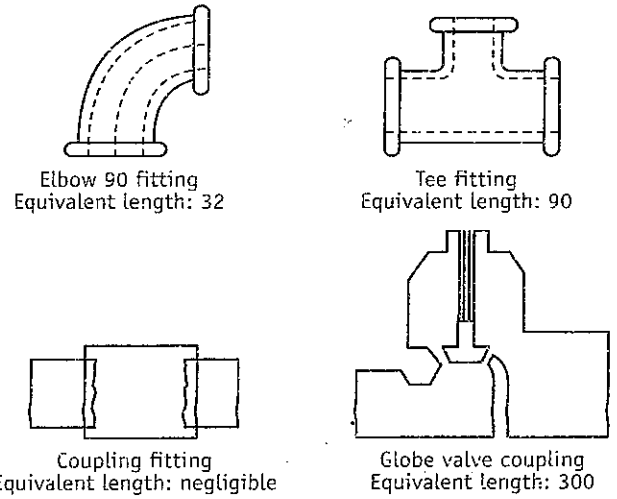


Figure 2-11. Friction losses in fittings of a new screwed pipe.

Losses in fittings, by convention, is expressed in terms of an **equivalent length of straight pipe**, which is given as a certain number of pipe diameters.

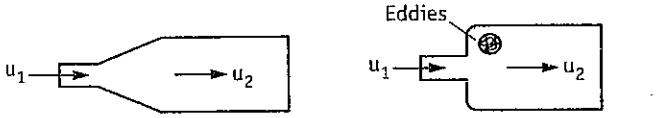
Equivalent lengths for a few screwed fittings are shown in Figure 2-11. For example, a globe valve is fitted in a pipeline having an internal diameter of 50 mm. Globe valve has an equivalent length of 300. Then,

equivalent length of this fitting = 300 × 50 = 15000 mm or 15.0 m.

That means the contribution of a globe valve is equivalent to 15 metres of a straight pipe towards the losses. This length is added to the straight section of the pipe and substituted in the Fanning equation (25) to obtain energy losses due to fittings.

Enlargement Losses

If the cross section of the pipe enlarges *gradually*, the fluid adapts itself to the changed section without any disturbance. Therefore, there is no loss of energy at this point.



(a) Gradual enlargement
No loss of energy

(b) Sudden enlargement
Loss of energy

If the cross section of the pipe changes suddenly, loss of energy is observed due to eddies. These are greater at this point than straight pipe. Due to these disturbances, the loss of head will be observed. In sudden enlargement, the velocity of flow at larger cross-section is less than the velocity at smaller cross-section, i.e. $u_2 < u_1$. For sudden enlargement, the loss is represented by:

$$\text{Sudden enlargement losses: } \Delta H_e = \frac{(u_1 - u_2)^2}{2g} \qquad ...(27)$$

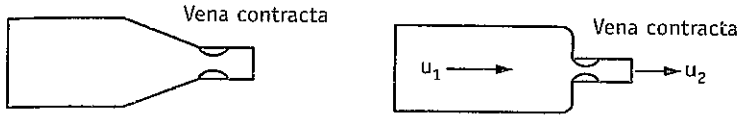
where ΔH_e = loss of head due to sudden enlargement, m

Contraction Losses

If the cross section of the pipe is reduced suddenly, the fluid flow is disturbed. Normally, the diameter of the fluid stream would be less than the initial value of the diameter. This point of minimum cross section is known as vena contracta. The velocity of fluid at smaller cross-section will be far greater than that at larger cross-section, i.e. $u_2 > u_1$. Then, u_1 may be considered negligible. The losses due to additional eddying are observed. Such contraction losses can be expressed as:

$$\text{Sudden contraction losses: } \Delta H_c = \frac{Ku_2^2}{2g} \qquad ...(28)$$

where ΔH_c = loss in head due to sudden contraction, m
K = constant
u_2 = velocity, m/s



(a) Gradual contraction
No loss of energy

(b) Sudden contraction
Loss of energy

The constant K depends on the relative areas of two sections. For example, when the ratio of the areas is 0.5, K is equal to 0.3. For a round entrance, K value for turbulent flow is about 0.04. For laminar flow, the loss is negligible.

MEASUREMENT OF RATE OF FLOW OF FLUIDS

Whenever fluids are used in a process, it is necessary to measure the rate at which the fluid is flowing through the pipe. This is required for optimization of process parameters in a chemical industry. Measurements are required for the calculation of auditing, e.g. town planning of water supply) and cost of usage (e.g. cost of water used in the houses). Methods of measurement may be classified as:

1. Direct weighing or measuring
2. Hydrodynamic methods
   (a) Orifice meter (b) Venturi meter
   (c) Pitot tube (d) Rotameter
3. Direct displacement meter

Some of the above mentioned meters are discussed in the following sections.

Direct Weighing or Measuring Meters

The liquid flowing through a pipe is collected for a particular period at any point and weighed or measured. Thus, rate of flow can be determined. Gases cannot be weighed. On commercial scale, it is not convenient to weigh the liquids. Therefore, these methods are impracticable.

Orifice Meter

Principle : The orifice meter is a thin plate containing a narrow and sharp aperture. When a fluid stream is ss fluid at the orifice meter increases compared to the velocity of the fluid in the upstream. This results in cor-

responding decrease in the pressure head. Bernoulli's theorem provides the basis for correlating the increase in the velocity head with the decrease in the pressure head between two points. The difference in the pressure head (ΔH) may be read from a manometer. If the diameter of the orifice is small compared to the diameter of the pipe, velocity of the fluid at the point before entering the orifice may be considered negligible. In such cases the manometer reading directly gives the velocity of the fluid.

The velocity of the fluid at the thin constriction may be written as:

$$u_o = \sqrt{2g.\Delta H} \qquad ...(29)$$

where u_o = velocity of fluid at the point of orifice meter, m/s
C_o = a constant
ΔH = difference in head from manometer, m

The ΔH can be measured using a manometer, which is connected to the pipe section between the initial stage and the orifice section. It can be substituted in equation (29) in order to get the velocity of the liquid flowing through the orifice. When cross-section of the pipe is known, the volume of the liquid flowing per hour can be determined.

Construction : The orifice meter is considered to be a thin plate containing a sharp aperture through which a fluid flows. Normally, orifice plate is placed between long straight pipes, so that other fittings do not alter the flow rate that is being measured. Although it is possible to place orifice meter in the side or bottom, for the present discussion, the plate is introduced into the pipe (Figure 2-12). A manometer is connected at points A and B as shown in Figure 2-12.

Working : Orifice meter is referred to as *variable head meter*, i.e. it measures the variation in the pressures across a fixed constriction placed in the path of flow consisting of a constant area.

When fluid stream is allowed to pass through the cross-section of the orifice, the velocity of fluid at point B increases at the expense of pressure head. As a result, the pressure at point A is higher than at point B. Bernoulli's equation provides the basis for correlating the increase in velocity head with the decrease in pressure head. The difference in pressure (ΔH metres) may be read from a manometer, connected to the points A and B as shown in Figure 2-12.

Bernoulli's equation may be applied for two points (A and B) for the given experimental conditions, as given below:

$$\sqrt{u_o^2 - u_A^2} = C_o\sqrt{2g.\Delta H} \qquad ...(30)$$

where u_o = velocity of fluid at the point of orifice meter, m/s

u_A = velocity of fluid at the point A, i.e. before orifice meter, m/s
C_o = a constant
ΔH = difference in head, m

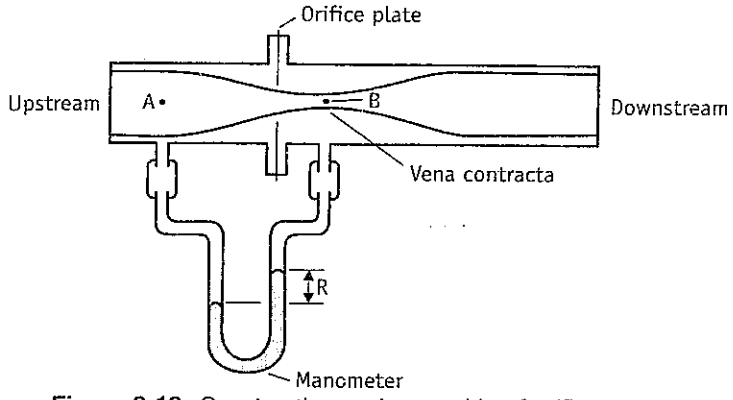


Figure 2-12. Construction and assembly of orifice meter.

If the diameter of the orifice is 1/5th of the pipe diameter or less, u_A is small compared to u_o. Then, u_A term may be neglected. Then equation (30) becomes:

$$u_o = C_o\sqrt{2g.\Delta H} \qquad ...(29)$$

ΔH can be measured using a manometer. It can be substituted in equation (29) in order to get the velocity of liquid flowing through orifice pipe. When cross-section of the pipe is known, the volume of liquid flowing per hour can be directly determined.

Mathematical treatment : Consider a fluid flowing through a pipe at a certain velocity (u_A). If the edge of orifice is sharp, fluid does not lose the velocity at once, while passing through the orifice. Two points A and B on either side of the orifice meter are chosen and Bernoulli's equation is applied. The Bernoulli's equation is:

$$\frac{P_A}{g\rho_A} + X_A + \frac{u_A^2}{2g} - F + W = \frac{P_B}{g\rho_B} + X_B\,\frac{u_B^2}{2g} \qquad ...(23)$$

In equation (23), the following assumptions may be made based on the working of orifice meter (Figure 2-12).

(1) Let the sections of pipe be horizontal, so that the heights (metres) of the points A and B are same (Figure 2-12). Then, two X terms are identical and get cancelled.

(2) Let the friction losses will not be appreciable and considered negligible. Then, F term becomes zero.

(3) The fluid flowing through the orifice is the same. Therefore, ρ_A is equal to ρ_B and can be termed simply ρ.

(4) No work is being done on the liquid or by the liquid, since no pump is used. Therefore, w term is equal to zero.

Substituting these terms in equation (23) gives an equation, which can be rearranged as follows.

$$\frac{P_A}{g\rho} + \frac{u_A^2}{2g} = \frac{P_B}{g\rho} + \frac{u_B^2}{2g}$$

$$\frac{1}{2g}(u_B^2 - u_A^2) = \frac{1}{g\rho}(P_A - P_B)$$

$$u_B^2 - u_A^2 = \frac{2g}{g\rho}\Delta P \qquad ...(31)$$

$$u_B^2 - u_A^2 = \frac{2g}{g\rho}\Delta P \qquad ...(32)$$

From the principles of statics, $(\Delta P/g\rho) = \Delta H$ in metres. Introducing this term in equation (32) gives:

$$u_B^2 - u_A^2 = 2g.\Delta P$$

$$\sqrt{u_B^2 - u_A^2} = \sqrt{2g.\Delta H} \qquad ...(33)$$

Normally, the diameter of the fluid stream would be less than the diameter of the orifice (Figure 2-8). This point of minimum cross section is known as the *vena contracta*. Though the pipe is full of liquid on both sides of the orifice, still the *vena contracta* exists and is surrounded by swirling liquid. Point B is chosen at the *vena contracta*.

In practice, the diameter of the stream at the *vena contracta* is not known, but that of the orifice diameter is known. A constant, C_o, is, therefore, included in equation (33) in order to correct the differences between velocities at orifice and at *vena contracta*. Therefore, equation (33) may be modified in terms of the velocity through the orifice (u_o).

$$\sqrt{u_o^2 - u_A^2} = C_o\sqrt{2g.\Delta H} \qquad ...(30)$$

The constant C_o also includes some losses due to friction. It depends on the construction (ratio of the orifice diameter to the pipe diameter and position of the orifice taps) and the nature of flow of liquid (Reynolds number).

If the diameter of the orifice is 1/5th of the pipe diameter or less, u_A is small compared to u_o. Then, u_A term may be neglected. Then equation (30) becomes:

$$u_o = C_o\sqrt{2g.\Delta H} \qquad ...(29)$$

where u_o = velocity of fluid at the point of orifice meter, m/s
C_o = a constant, a coefficient related to discharge
ΔH = difference in head, m

ΔH can be measured in metre using a manometer. It can be substituted in equation (29) to get the velocity of liquid flowing through orifice pipe. When cross section of the pipe is known, the V/h (volume of liquid flowing per hour) can be directly determined.

After passage through the orifice, the liquid flow gets disturbed which need to be quite (dissipated). It occurs when of most of the excess kinetic energy is turned into heat. The permanent loss of heat is therefore high, ultimately reaching a differential head produced within the meter.

Applications : Equation (30) is useful to determine:

(1) velocity at either of the points A or B. Ratio of u_o and u_A can be related to ratio of the area of the orifice to the area of the pipe, which is normally known.

(2) volume of the liquid flowing per hour when u_A and cross-section of the pipe are known.

Venturi Meter

Principle : Venturi meter consists of two tapered sections in the pipeline with a gradual constriction (throat) at its centre. When fluid stream is allowed to pass through the narrow throat, the velocity of the fluid increases at the venturi compared to the velocity of the upstream. This results in corresponding decrease in the pressure head. Bernoulli's theorem provides the basis for correlating the increase in the velocity head with the decrease in the pressure head between two points. The difference in the pressure head (ΔH) may be read from a manometer. If the diameter of the venturi is small compared to the diameter of the pipe, velocity of the fluid at the point before entering the venturi may be considered negligible. In such cases, the manometer reading directly gives the velocity of the fluid.

The velocity of the fluid at the narrow constriction (throat) may be written as:

$$u_v = C_v\sqrt{2g.\Delta H} \qquad ...(34)$$

where u_v = velocity at the throat of the venturi, m/s
C_v = coefficient of the venturi meter
ΔH = difference in head from manometer, m

ΔH can be measured using a manometer. It can be substituted in equation (34) in order to get the velocity of the liquid flowing through the venturi. When the cross section of the pipe is known, the volume of liquid flowing per hour can be determined.

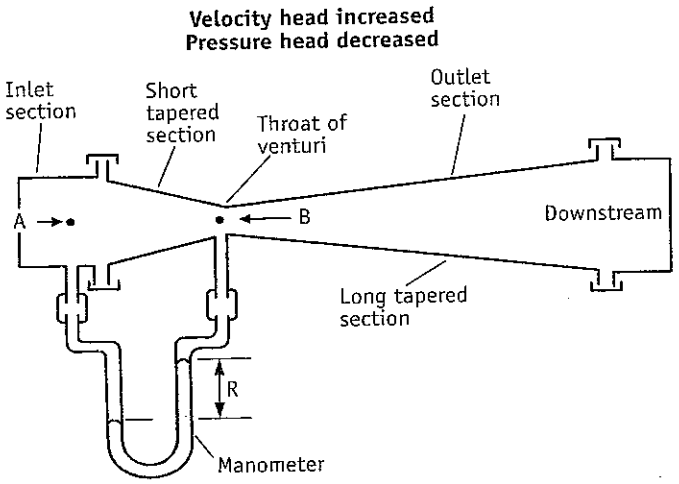


Figure 2-13. Construction of a venturi meter.

Construction : A venturi meter consists of two tapered sections inserted in a pipeline (Figure 2-13). Normally, venturi meter is placed between long straight pipes, so that other fittings will not alter the flow rate that is being measured. The upstream cone is normally shorter than the down stream. The tapers are smooth and gradual. Therefore, eddies in the down stream are absent and no power loss is observed. In addition, the cross section of the high velocity part of the stream is well defined. A manometer is connected at points A and B as shown in Figure 2-13.

Working : Venturi meter is referred to as variable head meter, i.e. it measures the variable differential pressure across a fixed constriction placed in the path of flow. In a venturi meter, the velocity of the fluid is increased at the throat, due to the constriction. This results in decreased pressure in the up-stream cone. The pressure drop in the upstream cone is utilised to measure the rate of flow using a manometer. Venturi meter nearly confirms the theoretical equations obtained for an orifice meter. On similar lines of equation (30), an equation for venturi meter may be written as:

$$\sqrt{u_v^2 - u_A^2} = C_v\sqrt{2g.\Delta H} \qquad ...(35)$$

where u_v = velocity at the throat of the venturi, m/s
u_A = velocity at point A (venturi throat), m/s
C_v = coefficient (= 0.98)

For a well-shaped constriction (circular cross-section), the constant (C_v) vary between 0.95 and 0.99 for turbulent flow. The value is much lower in laminar flow, because the kinetic energy correction is large. If the diameter of the smaller section is one-fifth of the pipe diameter or less, u_A^2 is considered to be small compared to u_v^2. Therefore, u_A^2 term may be disregarded. A simplified form of equation (35) is:

$$u_v = C_v\sqrt{2g.\Delta H} \qquad ...(34)$$

The difference in pressure (ΔH) can be read in metres directly from the manometer. Thus velocity of the flow may be measured. The value given by the venturi meter is average velocity of the flow. The divergent section is designed to induce a gradual return to the original velocity. This minimizes the eddy formation and permits the recovery of large proportion of the increased kinetic energy into the pressure energy. This forms the basis for a flow measuring device, venture meter. The velocity then decreases and the original pressure is recovered in the down stream cone.

Applications : Venturi meter is commonly used for liquids, especially water. It can also be used for the measurement of gases.

Disadvantages : (1) Venturi meter is expensive. (2) Venturi meter occupies more space. (3) The ratio of throat diameter to pipe diameter cannot be changed.

Differences between orifice and venturi meters : The differences between orifice and venturi meters are explained in Table 2-1.

TABLE 2-1
Differences Between Orifice Meter and Venturi Meter

	Orifice meter	*Venturi meter*
(1)	Cheap	Expensive
(2)	Easy to install	Fabrication is highly technical
(3)	Construction can be made at home	It should be purchased from the instrument dealer
(4)	Head losses are more	Head losses are insignificant
(5)	Power losses are more particularly on fluid that is carried for long periods of time	Power losses are less, hence coefficient of discharge is high
(6)	Normally used for testing purposes	Used in on-line installation
(7)	Greater flexibility	Not flexible, permanent
(8)	Reading of the orifice meter is larger under orifice meter is larger under identical conditions	The reading of venturi meter is comparatively smaller under identical conditions

Pitot Tube

Principle : Pitot tube consists of a sensing element with a small constriction compared to the size of the flow channel. When the sensing element is inserted at the centre of the stream, the velocity of flow is increased. This results in decreased pressure head. Tube at right angles to the flow measures pressure head only. The tube that pointed upstream measures pressure head and velocity head. The difference in the above readings indicates the velocity head.

According to Bernoulli's equation, velocity head of the fluid may be obtained using equation (36).

$$\Delta H_p = \frac{u^2}{2g} \qquad ...(36)$$

where u = velocity of the flow at the point of insertion, m/s

ΔH_p = difference in head from manometer, m

Therefore, the reading (R) of the manometer measures the velocity head in metres.

Construction : The construction of a pitot tube is shown in Figure 2-14. Pitot tube is also known as insertion meter. The size of the sensing element is small compared to the size of the flow channel. The point of measurement may be at the centre of the channel. One tube is perpendicular to the flow direction and the other tube is connected parallel to the direction of flow. The two tubes are connected to the legs of a manometer or a suitable device.

Working : Two tubes are inserted into the pipe in the manner shown in Figure 2-14. Pitot tube is used to measure the velocity head of the flow. In this tube, the velocity of fluid is increased at the narrow constriction. This results in decreased pressure. Tube at right angles to the flow measures pressure head only. The tube that points upstream measures pressure head and velocity head. The difference in the above readings indicates velocity head. Therefore, the reading (R) of the manometer measures the velocity head.

As seen in the Bernoulli's equation, velocity head of the fluid (ΔH_p) may be obtained from an equation similar to equation (29), which can be represented as:

$$u^2 = 2g.\Delta H_p$$

This is the theoretical velocity. Actual velocity is given by:

$$u^2 = C_v\sqrt{2g.\Delta H_p} \qquad ...(37)$$

where C_v = coefficient of pitot tube

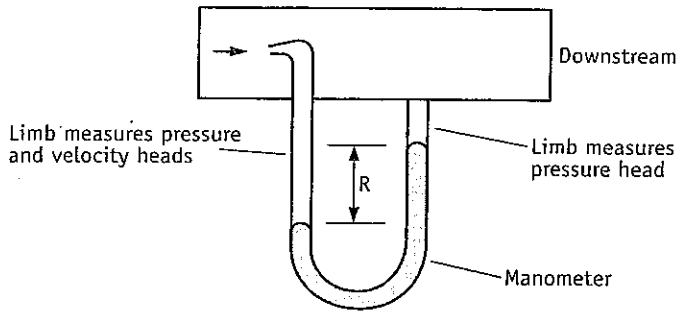


Figure 2-14. Construction and assembly of pitot tube.

Normally, pitot tube measures the velocity at one particular point, i.e. at the point of insertion. The average velocity (across the cross section of the pipe) may be obtained by either ways.

(a) Pitot tube may be inserted at the centre of the pipe and it measures the maximum velocity. Average velocity may be calculated from this maximum by means of calibrated charts.

(b) Adjustable pitot tube may be used to take readings from different points in the cross section. Mean velocity may be found by graphic integration. It is a difficult process.

Advantages : Pitot tube measures the velocity at one point only.

Disadvantages:

(1) The pitot tubes themselves cause more disturbance. Eddies within the pressure tube disturb the readings.

(2) They do not give average velocity directly.

(3) For gases, the reading is extremely small. For gases working on low pressure, some form of multiplying gauges must be used.

Rotameter

Rotameter is a *variable area meter*, i.e. it measures the area of flow, so as to produce a constant head differential. Therefore, rotameters are known as *area meters*.

Principle : Rotameter consists of a vertical, tapered and transparent tube in which a plummet is placed. During the fluid flow through the tube, the plummet rises and falls because of variation in flow. As a result, the area of the annular space between the plummet and the tube varies. The head loss across the annulus is equal to the weight of the plummet. The upper edge of the plummet is used as an index to note the reading on the tapered tube. This value indicates the flow of the fluid.

Construction : Rotameter consists of a vertical tapered tube, which is mounted with a narrow end down (Figure 2-15). The tube is usual-

ly made of glass on which a linear scale is etched. A solid plummet is placed in the tube. The diameter of the plummet is smaller than the narrow end of the tube. Rotameters are available with electric and electronic transmitters for recording. Floats of different densities are available, so that a 200-fold range of flow can be measured accurately. Floats may be made of lead, aluminium, glass and plastic.

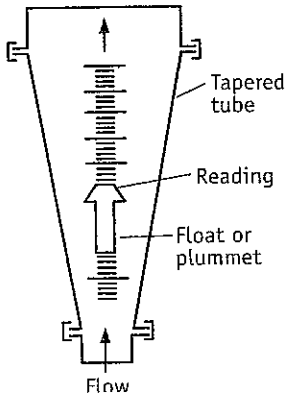


Figure 2-15. The Construction of a rotameter.

Working : As the flow is upward through a tapered tube, the flow of fluid varies. The plummet, which is surrounded by the fluid, rises and falls depending on the rate of flow. The greater the flow rate, the higher the plummet rises in the tube. In rotameters, the pressure drop is constant or nearly constant.

During the fluid flow, the area of the annular space between the plummet and the tube varies. Therefore, the head loss across the annulus is equal to the weight of the plummet. The flow may be read using the upper edge of the plummet as an index. The area is properly calibrated to the flow rate. The reading may be transmitted for recording, integrating and controlling.

Normally, manufacturers supply the necessary data and charts along with the meter while purchasing the instruments.

Uses : Rotameters are extensively used in chemical industries, such as bulk drugs. In the fermenters, the supply of air is controlled through rotameters. Rotameters are satisfactory both for gases and for liquids at high and low pressures.

Advantages:

(1) Operator has a direct visual index of flow reading. It is satisfactory for manual control of processes for experimental work.

(2) It does not require the condition that straight pipes should run before and after the meter.

Direct Displacement Meter

Displacement meter is used for measuring domestic water supplies. This has the advantage that the total volume of liquid that has passed can be read directly.

Principle : Displacement meters are used for measuring the flow rate of fluids in small lines. In these meters, a stream of water enters the meter and strikes the moving member (disc as in disc meters or buckets as in current meters). The rate of rotation of the moving member is proportional

to the velocity of water passing through the meter. The displacement of moving member is transmitted through a train of gears to the counting dial, which is present in the top of the member.

Advantages : The displacement meters have an advantage over venturi or orifice meters in the sense that the reading represents the total volume of fluid that has passed. This volume divided by a definite period gives the flow rate.

Comment 2-6. Differentiate between constant pressure and constant area meters.

Comment 2-7. Why are rate meters frequently used in chemical industries?

Comment 2-8. What is the difference between rate meter and quantity meter?

Comment 2-9. What should be the ideal diameter of the orifice in the measurement of fluid flow?

Comment 2-10. In a rotameter, the term 'float' indicates the lower density of the plummet over the flowing the fluid. True or false. Explain.

Summary

Fluid flow is concerned with the study of flow of liquids and gases (incompressible). The behavior of fluids influence the heat transfer, the size of equipment needed for handling in the manufacturing and type of pipes required for the transportation. The fluid mechanics deals with the behavior of fluid at rest as well as in motion, i.e. fluid statics and fluid dynamics.

Fluid statics deals with fluids at rest in equilibrium. The fluid at rest exerts pressure and it varies with layers at various heights. The pressure is expressed with reference to the atmospheric pressure employing manometers. Since pressure is exerted in terms of height, it is often referred to as head, i.e. pressure head. Three different manometers namely simple, differential and inclined manometer are employed, depending on the level of pressure difference to be measured. If the pressure difference is high, mercury manometers are used. Differential manometer are suitable for the measurement so small pressure differences. Inclined manometers are used to measure minute pressure differences. Special type of mercury gauges can also be used. Mechanical pressure gauges are also available, with circular dial for indicating the pressure. These manometers are employed in conjunction with flow meters to study the fluid dynamics.

Fluid dynamics deals with the study of fluids in motion. This study provides information on flow behaviour on the application of stress. Flow properties are used as an important quality control tools for maintaining the superiority of the liquid dosage forms. The macroscopic properties are relevant in engineering. Reynolds experiment indicates that whether a given fluid flow is laminar ($R_e < 2100$) or turbulent ($R_e > 4000$). Reynolds number (R_e) is a dimensionless number and has application in evalu-

ation of physical stability of suspensions and emulsions and heat transfer in liquids. When the fluid is under motion, it experiences several types of forces, but the net effect is evaluated, which is codified into Bernoulli's theorem. During the flow, the fluid at one point experiences: pressure energy, potential energy and kinetic energy. During the flow, at a different point, the same types of energies are experienced by the fluid. In addition, for the flow to occur, a pump is used, which adds (gives) certain amount of energy. Further, during the flow, the liquid looses certain energy due to frictional forces. As per the Bernoulli's theorem, the total energy per unit mass at any point remains constant, under steady state ideal flow. Thus, by accounting all the forms of energies, energy balance is obtained. Bernoulli's equation (energy balancing) permits the evaluation of the loss of energies due to friction, fitting, contraction and enlargement. Bernoull's theorem is applied for the measurement of the rate of flow using orifice meter, venture meter, etc.

The flow rate of fluid is an important *process parameter*. Flow rate may be expressed as volume/time, *L/h*. Flow rate can be obtained by collecting and weighing the liquid collected during a certain period of time. Flow rate can be obtained using Bernoulli's theorem and the apparatus; orifice meter, venture meter and pitot tube. Orifice meter is a plate containing a narrow and sharp aperture. Venturi meter is a tapered section in the pipeline with a gradual constriction (throat) at the centre. In these apparates, the velocity of the fluid at the constriction increases compared to the velocity of the fluid in the upstream. This results in corresponding decrease in pressure head, which is measured using a manometer. The manometer reading directly gives the velocity (volume/time) head. Pitot tube is used to measure the velocity head. Rotameter is a vertical tapered and transparent tube in which a plummet is placed. The upper edge of plummet is used to identify the reading. These are used extensively in chemical industries and in fermenters. Displacement meter are also used for measuring the rate of flow in domestic water supplies, particularly in small lines. Flow is identified from a counting dial as volume. The volume divided by the time gives the flow rate. These measurements are required for the calculation of auditing (town planning), cost of usage and adjusting process parameter in a chemical reaction.

Glossary of Symbols

C_o = Constant for the orifice meter.
C_p = Constant for the pitot tube.
C_v = Constant for the venturi meter
D = Diameter of the pipe, m.
η = Viscosity of the liquid, Pa·s.
f = Friction factor.

g = Acceleration due to gravity, m/s^2.
h_1 = Height of the liquid column at a point, m.
ΔH = Loss of head, m.
ΔH_e = Loss of head due to sudden enlargement, m.
ΔH_c = Loss of head due to sudden contraction, m.
ΔH_p = Difference in head from manometer in pitot tube, m.
Δh = Height difference between two points, m.
L = Length of pipe, m.
m = mass, kg.
P = Pressure, Pa.
P_s = Pressure on the column of a liquid, Pa.
ΔP_f = Pressure difference due to friction, Pa.
Q = volume flowing in unit time, t, L.
R_e = Reynolds number.
ρ = Density of the liquid, kg/m^3.
S = Surface area of the liquid column, m^2.
u = Velocity of the fluid in pipes, m/s.
w = Energy head added by the pipe, J.
w = work done, J.
X = Height of the liquid pipe from horizontal datum, m.

QUESTION BANK

Each question carries one mark

Note : Encircle the alphabet which corresponds to the single best response.

1. Which one the following is known as fluid?
   A. Always expands until it fills in the container
   B. Cannot be subjected to shear forces
   C. Cannot remain at rest under action of any shear forces
   D. Practically compressible
2. Which one of the following factors is responsible for frictional factor, f, of a rough pipe and turbulent flow?
   A. Relative roughness
   B. Reynolds number
   C. Reynolds number and relative roughness
   D. Size of the pipe and the discharge
3. Which one of these instruments is suitable for measuring minute pressure differences in a fluid?
   A. Diaphragm pressure gauge
   B. Inclined manometer
   C. Simple manometer
   D. U-tube differential manometer

4. Which type of head is measured using pitot-tube?
   A. Kinetic velocity head B. Pressure head
   C. Static velocity head D. Total head
5. Which one of the following is NOT covered under the definition of fluids?
   A. Gases B. Liquids
   C. Solids D. Vapours
6. Which one of the properties is responsible for the use of mercury in manometers?
   A. High surface tension B. High vapour pressure
   C. Low specific gravity D. Low vapour pressure
7. How many liquids are used in differential manometer?
   A. Four B. One
   C. Three D. Two
8. Which one of the following experiments is used for the study of flow of fluids?
   A. Bernoulis B. Orifice meter
   C. Reynolds D. Stokes
9. Reynolds number is indicative of one of the following.
   A. Fluid flow type B. Frictional factor
   C. Pumping rate D. Roughness of the pipe
10. Reynolds number depends on one of the following factors.
    A. Roughness of the pipe B. Surface area of the pipe
    C. Viscosity of the liquid D. Volume of the liquid
11. Pressure at a point in a static mass of liquid depends on one of the following factors.
    A. Depth below the free liquid surface
    B. Shape and size of bounding container
    C. Specific weight of liquid and depth below the free liquid surface
    D. Specific weight of liquid, depth below the free liquid surface and shape and size of the bounding container
12. The loss of head due to sudden enlargement in a pipe depends on one of the following differences.
    A. Diameters B. Flow rates
    C. Surface areas D. Viscosities
13. Reynolds number may be defined as the ratio of one of the following factors.
    A. Elastic forces to pressure forces
    B. Gravity forces to inertial forces
    C. Inertial forces to viscous forces
    D. Viscous forces to inertial forces

14. The velocity distribution of a fluid in a pipe is parabolic for one of the following types of flow.
    A. Non-uniform laminar flow B. Non-uniform turbulent flow
    C. Uniform laminar flow D. Uniform turbulent flow
15. In a pipe, laminar flow has a center line velocity of 0.1 m/s. What is the average velocity?
    A. 5 cm/s B. 10 cm/s
    C. 15 cm/s D. 20 cm/s
16. What is the unit for pressure energy in hydraulics?
    A. Joules B $Kg \times m/s^2$
    C. Metre D. Pascal
17. Two pipe systems are said to be equivalent in their lengths, in one of the following conditions.
    A. Both the systems are connected in series
    B. Discharge and diameter are same.
    C. Friction factor and discharge are same
    D. Same head loss is produced by the same discharge
18. In which portion of a pipe, the flow of liquid is high?
    A. At the actual surface of pipe wall
    B. Central portion
    C. Near the pipe wall
    D. Transition region
19. In the flow of fluids, the inertial forces depend on one of the following.
    A. Mass
    B. Mass and velocity
    C. Mass, velocity and density
    D. Mass, velocity, density and viscosity
20. Measurement of time of flow is important for the determination of flow of fluids in one of the following.
    A. Displacement meter B. Orifice meter
    C. Rotameter D. Venturi meter
21. Which of the following gives direct reading of flow of fluids?
    A. Orifice meter B. Pitot tube
    C. Rotameter D Venturi meter
22. Which one of the following does NOT require manometer in the construction of flow meters.
    A. Orifice meter B. Pitot tube
    C. Rotameter D. Venturi meter
23. Which one of these is having a single tapered section for the measurement of flow of fluids?
    A. Orifice meter B. Pitot tube
    C. Rotameter D. Venturi meter

24. Which one of the following uses a thin plate for the measurement of flow of fluids?
    A. Orifice meter B. Pitot tube
    C. Rotameter D. Venturi meter
25. Displacement meter is used to measure one of the following.
    A. Head loss of liquid B. Velocity of liquid
    C. Volume of liquid D. Weight of liquid
26. The fluid flow in which the fluid particles in one layer DO NOT mix with the fluid particles in the other layer is called as:
    A. laminar flow B. layer flow
    C. mixed type D. turbulent flow
27. The fluid particles flowing in a fluid follow one of the following.
    A. Constant velocity B. Variable velocities
    C. Velocity as high as possible D. Zero velocity
28. Which of the following can be considered as an ideal fluid?
    A. Compressible fluid B. Non-viscous fluid
    C. Plastic fluid D. Viscous fluid
29. Fluid is a substance which does NOT offer resistance to change one of the following. Identify.
    A. Flow B. Pressure
    C. Shape D. Volume
30. Which one of the following instruments is used for measuring the speed of a submarine moving in a deep sea?
    A. Orifice meter B. Pitot tube
    C. Rotameter D. Venturi meter
31. Alcohol is used in manometers because of one of the following properties?
    A. Clear visibility B. Low density
    C. Low surface tension D. Low vapour pressure

Each question carries 2 marks

1. Draw a labeled diagram of pitot tube and explain the working of the same.
2. What is the use of a pitot tube? Write its advantages and disadvantages.
3. Write the Fannings equation and explain the terms. What is its importance?
4. Express the Hagen-Poiseuille's relationship. What is its importance?
5. Explain the term 'head'. List the different heads in the Bernoulli's theorem.
6. What is meant by 'equivalent pipe length? What are its applications?
7. What is Reynolds number? Describe its importance.

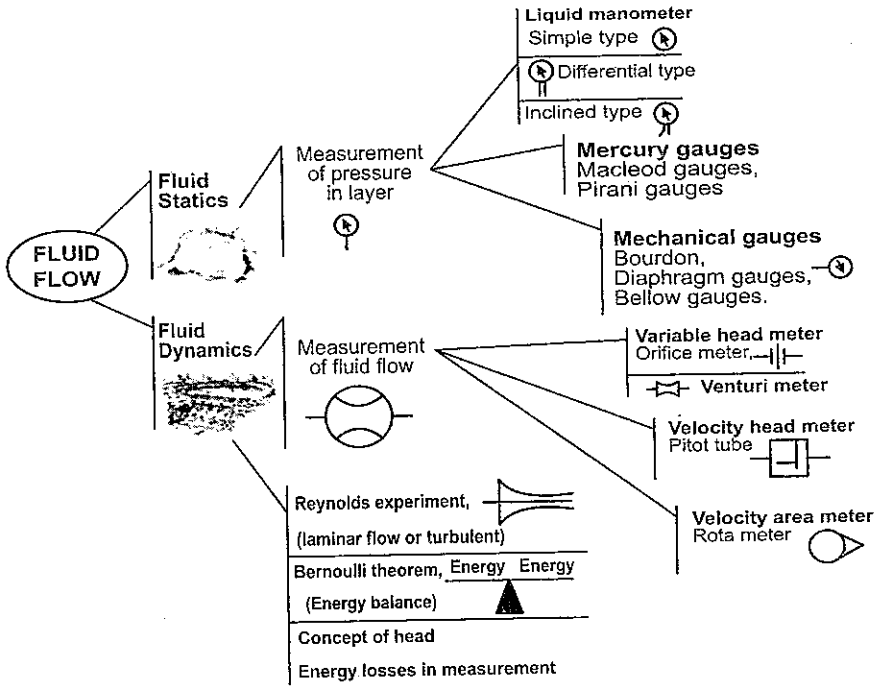
8. List the advantages and disadvantages of rotameter.
9. How are losses of energy due to enlargement in cross section measured? Give relevant equation and explain the terms.
10. Give Reynolds number and explain the symbols used therein.
11. What is a 'differential head meter'? Name some devices under this category.
12. What is a pressure head? How is it calculated?
13. What are vertical head meters? Describe one such meter.
14. Define mechanical pressures. Give the functioning of any one such gauge with a labeled diagram.
15. Explain the functioning of C-shaped Bourdon gauge with a labeled diagram.

Each question carries 5 marks

1. Describe the types of flow patterns exhibited by liquids in motion.
2. Differentiate fluid statics and fluid dynamics. Name the fluid flow meter, which gives point velocity.
3. Write Bernoulli's equation and explain the symbols used therein with a labeled diagram.
4. Describe Reynolds classic experiment elucidating different types of flow patterns, when a liquid flows through a closed channel.
5. Explain the characteristics of different types of flow. Add a note on Reynolds number.
6. Compare and contrast the advantages and disadvantages of pitot tube and rotameter.
7. What are the merits and demerits of venturi meter over orifice meter?
8. What is the condition of hydrostatic equilibrium? Obtain the barometric equation.

Each question carries 10 marks

1. Deduce relevant equations for calculation of flow rates using orifice meter.
2. Derive Bernoulli's equation stating the assumptions.
3. Give a neat sketch of two fluid manometers and explain its working principle.
4. Explain the working, principle and construction of venturi meter. Write the expression for the volumetric flow rate of fluid through it.
5. Explain the energy losses that occur when a fluid flows through a pipe with relevant equations.



MIND MAP OF FLUID FLOW

CHAPTER 3

Size Reduction

Mechanisms of Size Reduction
Modes of Stress Applied in Size Reduction
Classification of Size Reduction Equipment
Size Reduction Equipment
Selection of a Mill
Theories of Comminution
Energy of Comminution

LEARNING OBJECTIVES

After reading this chapter, the reader should be able to:

- Understand the principles of the size reduction, mechanisms involved, modes applied and applications.
- Explain the designs of industrial scale mills in terms of principles, working and uses.
- Select the size reduction equipment more scientifically based on the properties of materials, design of mills.
- Evaluate the efficiency of mills using relevant theories (Rittinger's, Bond's and Kick's) and equations.

Size reduction is a process of reducing large solid unit masses (vegetable or chemical substances) into small unit masses, i.e. coarse particles or fine particles.

Normally, pharmaceutical powders are *polydisperse*, i.e. consisting particles of different sizes. Polydisperse powders create considerable difficulties in the production of dosage forms. Particles of monosize (equal size) may be ideal for pharmaceutical purposes. In practice, powders with narrow range of size distribution can obviate the problems in processing them further. Size reduction alone is not sufficient to obtain mono-size or narrow size range powder. Therefore, size reduction and size separation are combined to obtain powders of desired size. (The fundamental aspects on powders, their characteristics and methods of evaluation are given in the book, "*Textbook of Physical Pharmaceutics-II*" by C.V.S. Subrahmanyam, Vallabh Prakashan, Delhi).

Size reduction process is also termed as *comminution* or *diminution* or *pulverisation*. Normally, size reduction may be achieved by two methods, namely precipitation or mechanical process.

In the ***precipitation method***, the substance is dissolved in an appropriate solvent. Subsequently, it is finely precipitated by the addition of another solvent, which is miscible with the first, but in the later the substance is insoluble. This method is suitable for the production of raw materials and bulk drugs. Inorganic chemicals, such as calcium carbonate, magnesium carbonate and yellow mercuric oxide, are prepared by precipitation method. Other methods are crystallization and drying a fine spray of solution.

In the ***mechanical process***, the substance is subjected to mechanical forces using grinding equipment (e.g. ball mill, roller mill, hammer mill, etc.). In general, dry grinding or milling is used in the production of tablets and capsules, while wet grinding is used in the preparation of suspensions, emulsions and ointments. The method of milling is applied either in the production of raw materials or as a part of the production cycle in the manufacture of dosage forms.

Size reduction of substances offers several **advantages**. These are as follows:

Content uniformity : Mixing of different ingredients can be effective, if the particle size is uniform and small. Size reduction ensures this objective. As the size of particles is small, the number of particles per unit weight (dose) is large. The larger the number of particles, the better is the mixing. Thus, better content uniformity can be obtained for a given dose. This is particularly important in formulations containing potent and low dose drugs.

Uniform flow : Smaller particle size and controlled size distribution promote the flow of the powder into dies during compression of tablets. The same principles are used in the production of capsules.

Effective extraction of drugs : Smaller particles allow rapid penetration of menstruum or solvent into the tissue or cells of vegetable and animal origin (liver and pancreas). As a result, extraction or leaching of active constituents becomes effective and complete in preparation of galenicals. The time required for extraction can be shortened. For example, pancreas is subjected to grinding action for the extraction of insulin.

Normally, fine powders are preferred for compound powders, while moderately coarse powders are used for the preparation of tinctures. Coarse powders without fines are employed in percolation process.

Effective drying : Drying of a granular mass can be rapid and effective, if the size of granules is small and uniform. Such techniques are used in the production of tablets. Similarly drying of medicinal plant parts can be quick and fast after size reduction.

Improved physical stability : In case of suspensions and emulsions, the rate of sedimentation decreases to a large extent if particle size is small.

Improved dissolution rate : Size reduction increases surface area, which facilitates intimate contact of solid particles and gastric or intestinal juices. Thus, the rate of dissolution enhances. For example, size reduction of griseofulvin led to the development of oral tablet with a dose half that of the originally marketed product. In case of insufflations (preparations inhaled directly into the lungs), the drug should be usually smaller than 5 μm. Micronized powder of aspirin is used in the preparation of tablets, microfined aspro (analgesic and anti-inflammatory agent).

Improved rate of absorption : The smaller the particle size, the faster is the absorption, because of enhanced dissolution. Chloramphenicol has been shown to absorb faster when given with particle size of 50 μm compared to particle size of 400 μm. Keeping in view of the advantages, pharmacopoeia specifies particle size as a quality control tool. For example, griseofulvin (antifungal antibiotic) should have surface area of not less than 1300 to 1700 m^2/kg (as per IP). If it is less, the absorption of the drug decreases. Sulphonamides attain their antibacterial activity at powder sizes of about 1 μm or below. Increased antiseptic action has been demonstrated when the particle size of calomel has been reduced.

The **disadvantages** of size reduction process are as follows:

(1) *Drug degradation* : Drug decomposition is possible due to the heat produced during milling. Thermo-labile substances are the most affected. The increased surface area also facilitates drug decomposition owing to enhanced dissolution.

Cooling support systems are provided to decrease the heat in milling equipment. Drugs containing waxy materials become soft due to heat generated during milling. Therefore the feed is chilled before milling.

(2) *Poor mixing* : Normally, very small particles possess strong cohesive forces, hence, aggregation of particles is possible. Aggregation inhibits the effective blending of different additives. An increase in surface area may promote the adsorption of air, which may inhibit wettability of the drug during production. Therefore, optimum particle size is desirable to improve blending and to avoid poor mixing.

(3) *Contamination* : During milling and grinding, the grinding surfaces wear off (e.g. ceramic or iron equipment), the particles of

which are present as impurities in the powder. Such type of mills should be avoided, when drugs of high purity are required.

The importance of size reduction is so profound that it is used in the production of all dosage forms such as tablets, capsules, suspensions, emulsions, injections and galenicals. The principles of size reduction, construction and working of equipment are discussed in this chapter. The equipment, which are used in pharmaceutical industry, are given importance.

Comment 3-1. Why does size reduction of a powder give polydisperse particles, not monodisperse?

Comment 3-2. Size reduction of a material enhances the action of drugs. Explain.

MECHANISMS OF SIZE REDUCTION

The mechanism of size reduction may vary with the nature of material. Therefore, each drug may require a separate treatment. However, the general mechanisms may be described in Figure 3-1.

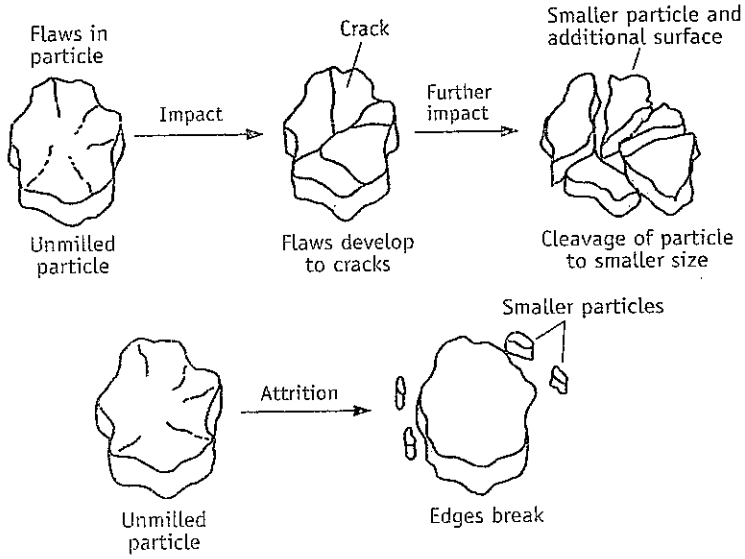


Figure 3-1. Mechanisms of size reduction.

The theoretical strength of a crystalline material can be calculated from interatomic attractive and repulsive forces. The strength of material in reality is found to be many times lesser than the theoretical value. This discrepancy is explained in terms of flaws of various kinds. The strength of material, therefore, depends on the distribution of flaws and is a statistical quantity varying within fairly wide limits.

Particles, be it amorphous or crystalline, will have flaws to a definite degree. These constitute weak parts in the particles. When sufficient stresses such as impact, shear and compression are applied, the weak flaws develop into cracks, which eventually lead to cleavage (Figure 3-1a). Thus, smaller particles are obtained with additional surface area.

When stress in the form of attrition is applied, the particle surfaces chip and produce small particles (Figure 3-1b).

Generally drugs are easy to grind. The operation is classified as fine grinding (#200) and superfine grinding (particles of few micrometre). Most of the pharmaceutical operations fall into these classes, although coarser grinding is applied to vegetable drugs before extraction.

Comment 3-3. Size reduction is not possible, if particles do not contain flaws/cracks. True or false. Justify.

MODES OF STRESS APPLIED IN SIZE REDUCTION

Stresses of varied nature are applied to achieve size reduction. The common modes of size reduction are explained as follows.

1. **Cutting :** The material is cut by means of a sharp blade(s). It is useful for comminution of fibrous or waxy solids. E.g. cutter mill.
2. **Compression :** In this mode, the material is crushed between rollers by the application of pressure. In compression, the applied stress do not cause failure directly on the particle, but generate distortion (form a crack tip) in a region away from the point of primary stress application. E.g. roller mill.
3. **Impact :** This involves the operation of hammers or bars at high speeds. When a lump of material strikes the rotating hammers, the material splits apart. This action continues until particles of required size are obtained. E.g. hammer mill.

   Impact also occurs when moving particles strike against a stationary surface. In the same way, particles moving at high speeds collide each other and produce smaller particles. E.g. fluid energy mill.
4. **Attrition :** This process involves breaking down of the material by rubbing action between two surfaces, i.e. surface phenomenon. It is generally necessary for fine grinding. E.g. fluid energy mill.

Although the predominant mode with one example of equipment is discussed above, normally more than one of these modes exhibit to some extent. The amount of deformation (or milling) is a function of stress, i.e. the rate at which the stress is applied as well as the time of application of stress. Thus fracture is a time dependent process. Stress application is complicated by two processes: free crushing and packed crushing.

- *Free crushing* : Stress is applied on an unconstrained particle and released when the failure occur.
- *Packed crushing* : Stress continues on the bed of particles that is already crushed. In other words, a part of solids do not get crushed if they are not crushed earlier. For this reason, the powder is sieved and the coarse particles are returned to the milling again. Then, size reduction occurs with less effort.

Different types of size reduction equipment are available, since materials have their own distinctive properties. For example, a powder produced by ball mill differs from that produced by hammer mill, even though both powders may be screened to the same fineness. The differences may be in terms of shape, roughness and their internal pore-structure of a particle.

CLASSIFICATION OF SIZE REDUCTION EQUIPMENT

A. Crushers, e.g. edge runner mill, end runner mill.

B. Grinders : (1) Impact mills, e.g. hammer mill.
(2) Rolling-compression mills, e.g. roller mill.
(3) Attrition mills, e.g. fluid energy mill.
(4) Tumbling mills, e.g. ball mill.

C. Ultrafine grinders, e.g. fluid energy mill.

D. Cutting machines, e.g. cutter mill.

Some of them are discussed individually in the following sections.

SIZE REDUCTION — EQUIPMENT

The equipment described in this chapter are also used in small-scale plants. The basic principles and working remain the same even in large-scale operations. Other variants are also included, in brief.

General Parts of Size Reduction Equipment

The milling or grinding equipment consists of three basic components. These are shown in Figure 3-2.

(1) A structure for feeding the material to the mill. It is called hopper.

(2) The milling chamber is the one in which actual size reduction takes place. It consists of a rotor and a stator.

(3) Receiver (discharge chute) in which the milled product is collected.

Other Accessories

(1) Sieves or screens are enclosed in the milling chamber to separate the particles by their sizes.

(2) Cyclone separator or centrifugation equipment is fitted to the mills for separation of particles by their sizes.

(3) Dust collectors are employed in order to collect the fine powder and dust that arise during milling process.

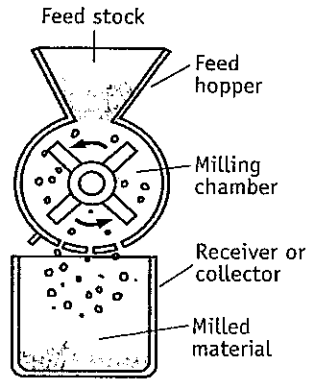


Figure 3-2. General parts of size reduction equipment. Three basic components.

Special Features

(1) Cooling devices are fitted to the chamber to reduce the heat produced during milling.

(2) A closed environment is desirable for milling hygroscopic substances. For this purpose, dehumidified air is necessary.

(3) Closed system with inert atmosphere (nitrogen or carbon dioxide) is desirable for milling of drugs, which are oxidisable or combustible. Similarly, material to be used in the production of parenterals should be milled under sterile environment.

Though general parts of the equipment are identical, several modifications have been incorporated in order to make the process easy to handle and to provide desired discharge.

Critical Quality Attributes — Milling with Size Separation

The critical quality attributes (CQAs) along with process parameters (PPs) are recorded in Figure 3-3. The milling (size reduction) is considered in the context of production of tablets, wet milling or dry milling. The upstream operation must be drying of granules and the downstream is size separation or blending. Normally, milling and size separation are conducted simultaneously. For a given set of conditions, the attributes related to content uniformity are critical: average size, size distribution, flow properties and densities.

The process parameters optimized as: feed rate, mill speed and time of milling. These are controlled during the milling and are prefixed as standards with limits for a given set of conditions. Production control charts are used for monitoring the standards. The above points mentioned are the general characteristics, but a few may change depending on the mill type.

Mortar and Pestle

This is the classical and the simplest equipment for grinding. In this method, the material is crushed by the application of attrition and pressure. The apothecaries used an array of metal, wooden and ceramic mortars and pestles for the production of pills. In this equipment, both mortar and pestle are rotating, whereas a scraper is static. Heavy pestles provide the force

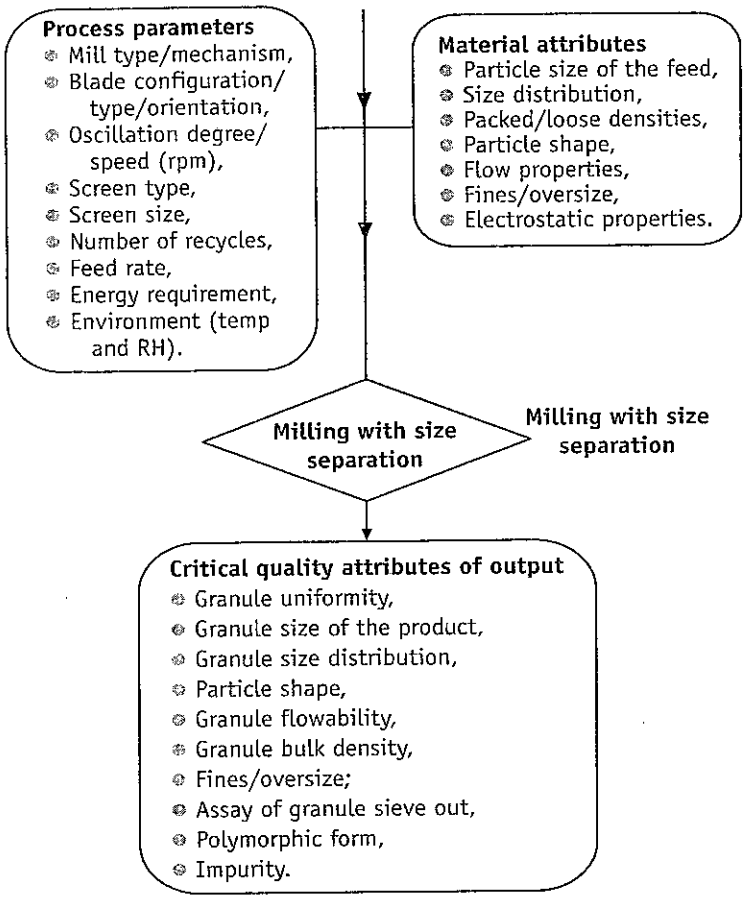


Figure 3-3. Process parameters and critical quality attributes for milling in the production of tablets— Milling with size separation.

of compression, which is an efficient process for wet grinding. This equipment cannot be provided with a sieve for continuous removal of fines.

Rotary Cutter Mill

Principle : In the cutter mill, size reduction involves successive cutting or shearing the feed material with the help of sharp knives.

Construction : The construction of a cutter mill is shown in Figure 3-4. The milling chamber consists of two types of knives, namely rotating knives and stationary knives. A horizontally mounted rotor disc consists of 2 to 12 knives spaced uniformly. The casing also has several stationary knives. The hopper is placed above it. The bottom of casing holds a screen

that controls the size of the material. Discharge chute is attached at the bottom of the mill.

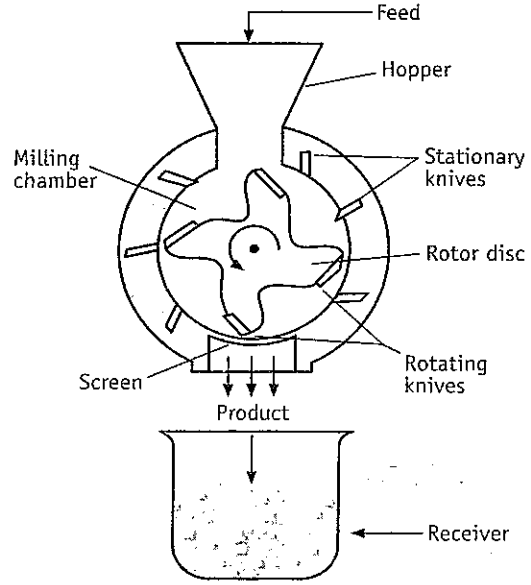


Figure 3-4. Cutter mill.

Working : The rotor disc is allowed to rotate at speeds from 200 to 900 rotations per minute. The feed material is loaded into the hopper, which flows down by the force of gravity. During the rotation of disc, the material comes very close between the stationary and rotating knives, thereby the material is cut into small pieces. Smaller particles pass through the screen. The knives lift the coarser particles up while rotating and promote further size reduction. The product is collected into a receiver.

The particle size and shape are determined by the rotor size, gap between the rotating and stationary knives and opening of the sieve.

Uses : Cutter mills are used for the size reduction (finer than 80 to 100 mesh) of tough and fibrous materials. Medicinal plant parts and animal tissues are normally converted into small parts. Soft materials such as roots, peels and wood are cut before extraction. It is also used in the manufacture of rubber, plastics, recycling of paper waste and plastic materials.

Variants : *Double-runner disc mill—It consists of two-vertical discs,* each rotating in opposite directions. Single runner disc mill—only one disc may rotate and the other is stationary. The disc may be provided with cutting faces, teeth or knives. Clearance between the discs may be adjusted to obtain the desirable particle size.

Roller Mill

Principle : The material is crushed (compressed) by the application of stress, though attrition also influences. Stress is applied by rotating heavy wheels, mullers or rollers.

Construction : The construction of a roller mill is shown in Figure 3-5. Roller mill consists of two cylindrical rollers made of stone or metal, which are mounted horizontally. Rollers can have a diameter ranging from a few millimetres up to a metre. Rollers are capable of rotating on their longitudinal axes. Generally, one of the rollers is driven directly using a motor, while the second one runs freely. The gap between the rollers can be controlled to obtain the desired particle size.

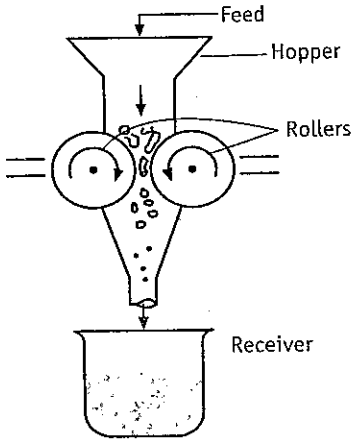


Figure 3-5. Roller mill.

Working : The rollers are allowed to rotate. The material is fed from the hopper into the gap between the two rollers. The material is crushed while passing through the rollers under high pressure. The clearance (gap) between the rollers can be adjusted to control the degree of size reduction. The product is collected into a receiver.

Uses : Roller mill is used for crushing and cracking of seeds before extraction of fixed oils. It is also used to crush soft tissue to help in the penetration of solvent during extraction process.

Variants : Multiple smooth rollers or corrugated, ribbed, or saw-toothed rollers can provide cutting action also.

Hammer Mill

Principle : The hammer mill operates on the principle of impact between rapidly moving hammers mounted on a rotor and the powder material.

Construction : The construction of a hammer mill is shown in Figure 3-6. The hammer mill can be either the horizontal or the vertical shaft type. Hammers are usually made of hardened steel, stainless steel with impact surface made of an extremely abrasive resistant material such as haystellite and carbaloy. Stainless steel hammers are sufficient for pharmaceutical purposes.

Hammers may take several shapes. Two basic shapes are the stirrup and the bar. Bar-shaped hammers are used extensively in tablet granulation. The hammer blades can be with flat edges or sharp edges or both on each side. Hammers may be either rigid or swing-type. Free swinging type has an advantage that there will be increasing clearance between hammers and screen, if excessive build occurs in the mill.

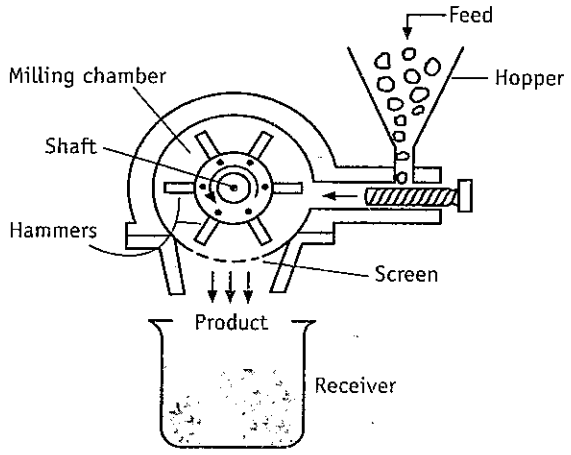
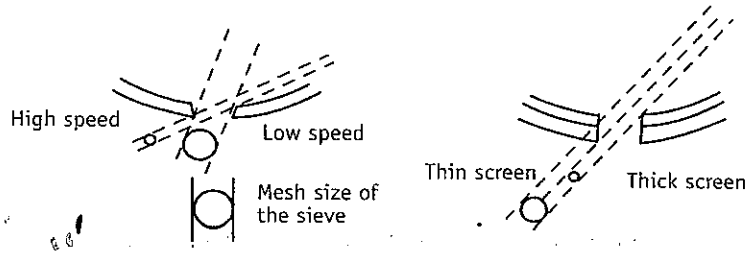


Figure 3-6. Hammer mill.

This unit is enclosed with a chamber containing a grid or removable screen through which the material must pass. These screens are not of woven type. Screens are prepared using metal sheet of varying thickness with perforated holes or slots.

Working : The hammers are allowed to be in continuous motion (8000 to 15000 rotations per minute). The feed material is placed into the hopper, which flows vertically down and then horizontally, while hammers are in continuous motion. These rotating hammers beat the material to yield smaller particles. Then, these particles pass through the screen. Due to the tangential exit, the size of the particles is considerably smaller (Figure 3-7b) than the aperture of the screen (Figure 3-7a).



(a) Influence of the speed on particle size

(b) Influence of the thickness of the screen on particle size

Figure 3-7. Size reduction modes in the hammer mill.

The screens are interchangeable, so that any grade of fineness can be achieved. The hammers act as a centrifugal fan, so that large amount of air is drawn through the mill. In most cases, this is sufficient to counteract the heat generated during milling. The fineness of the product can be regulated by altering:

- rotor speed,
- feed rate,
- clearance between hammers and grinding plates,
- number and type of hammers,
- size of the discharge opening (screen).

Uses : Fine to moderate grinding of powders may be obtained, depending on the speed of the hammer. The expected particle size may vary from 10 to 400 μm. Non abrasive to moderately abrasive, brittle materials can be used as feed stock. It is used to mill dry materials, wet filter press cakes, ointments, slurries, etc. Brittle material is best fractured by impact from blunt hammers; fibrous material is best reduced in size by cutting edges.

Advantages : (1) Hammer mill is easy to setup (install), dismantle and clean up.

(2) Scale-up problems are minimum provided same type of mill is used.

(3) Various types of feed stock can be handled using screen of different sizes.

(4) Hammer mill occupies small space.

(5) It is versatile, i.e. speed and screen can be changed rapidly.

(6) As it is operated in a closed environment, dust can be reduced and explosion hazards can be prevented.

Disadvantages : (1) The screens may get clogged.

(2) Heat buildup during milling is more, therefore, product degradation is possible.

(3) Wearing of mill and screen is more with abrasive materials.

(4) Hammer mills cannot be employed to mill sticky, fibrous and hard materials.

Variants : The examples of hammer mills used in pharmaceutical industry are:

(a) Fitzpatrick comminuting machine (Fitz mill)

(b) Stokes tornado mill

Fitz mill is used for drugs, roots, herbs, glands, livers and soaps.

Micropulveriser : Micropulveriser has been used for sugar, chemicals, pharmaceuticals and cosmetics. The construction is almost same as shown in Figure 3-6. The liner of the mill housing is made of multiple serrations, which promote the breakage of particles thrown against the wall by the rotating hammers. An air injection feeder can be used to project the feed directly in front of the hammer tips, which are fitted with tungsten carbide inserts. This arrangement increases mill efficiency.

Hammer crusher and *vertical impact pulveriser* work on the principle of impact for size reduction.

Ball Mill or Pebble Mill or Tumbling Mills

Principle : The ball mill works on the principle of impact between the rapidly moving balls and the powder material, both enclosed in a hollow cylinder. At low speeds, the balls roll over each other and attrition (rubbing action) will be the predominant mode of action. Thus, in a ball mill, impact or attrition or both are responsible for the size reduction.

Construction : The construction of a ball mill is shown in Figure 3-8. Ball mill consists of a hollow cylinder, which is mounted on a metallic frame in such a way that it can be rotated on its longitudinal axis. The length of the cylinder is slightly greater than its diameter. The cylinder is made of a metal and is usually lined with chrome. In pharmaceutical industry, sometimes the cylinder is lined with rubber or porcelain.

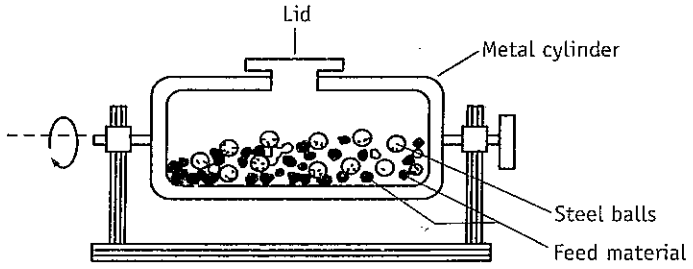


Figure 3-8. Ball mill.

The cylinder contains balls that occupy 30 to 50 % of the mill volume. The weight of the balls is kept constant. The ball size depends on the size of the feed and the diameter of the mill. Balls are made of steel, iron or stoneware. These act as the grinding medium.

Working : The drug to be ground is put into the cylinder of the mill in such a quantity that it is filled to about 60 % of the volume (material to void ratio). A fixed number of balls are introduced and the cylinder is closed. The mill is allowed to rotate on its longitudinal axis.

The speed of rotation is very important. At low speeds, the balls roll over each other and attrition will be a predominant mode of stress (Figure

3-9A). The use of small balls (or glass pebbles) is recommended so that the surface is the greatest. This mode of attrition is used for wet grinding. It may be useful to add surface active agents to prevent agglomeration.

At correct speed (critical speed), the centrifugal force just occurs, as a result the balls are picked up by the mill wall and carried nearly to the top, where they break contact with the wall and fall to the bottom. (Figure 3-9C). In this manner, impact stress is also induced and the size reduction is made effective.

At still higher speeds, the balls are thrown out to the wall by centrifugal force. Hence, grinding will not occur. The compression by the balls against the wall is not sufficient for effective comminution of the substance (Figure 3-9B).

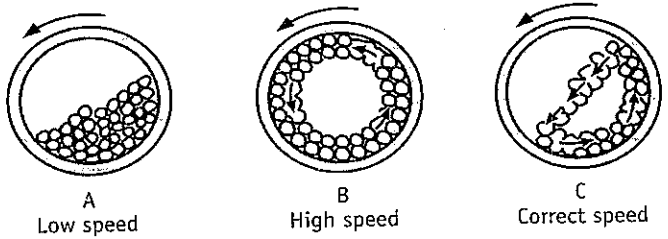
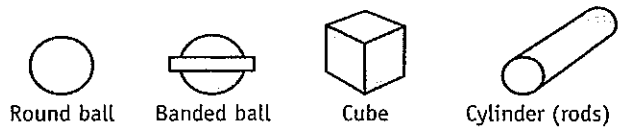


Figure 3-9. Modes of rolling of balls in the ball mill operations.

Uses : Fine grinding with a particle size of 100 to 5 μm or less can be obtained, particularly for hard and abrasive materials. Stainless steel balls are preferred in the production of ophthalmic and parenteral products, as there is a less chance of contamination due to wear. Ball mill at low speeds is used for milling dyes, pigments and insecticides.

Advantages : Ball mill offers several advantages and is widely used. These are:

(1) It can produce very fine powder.
(2) It is used for batch operation. It can be made continuous operation by including a chamber next to the cylinder. These are separated using sieves.
(3) Ball mill is suitable for both wet and dry grinding processes.
(4) Toxic substances can be ground, as the cylinder is a closed system.
(5) Since the mill is a closed system, sterility can be achieved.
(6) Milling operation can be accomplished in an inert atmosphere, if oxygen sensitive substances are to be milled.
(7) Balls can be of various shapes and sizes. Rods or bars may be used instead of balls. Rod mill is particularly useful for milling of sticky materials.



Commonly used balls

(8) In ball mill, installation, operation and labour costs are low.

Disadvantages : Some of the disadvantages are:

(1) The ball mill is a very noisy machine.
(2) Wear occurs from the balls as well as from the casing, which may result in contamination of the product.
(3) Ball milling is a slow process. The rate at which energy can be applied is limited, because it depends on the acceleration of the balls, which is influenced by the gravitational force.
(4) Soft, tacky, fibrous material cannot be milled by ball mill.

Variants : (a) **Hardinge mill :** Usually, Hardinge mill consists of hollow cylinder with a conical central section. Different sized balls are used. The small balls are placed near the discharge end, where they can perform the finest grinding. The largest balls remain in the cylindrical feed-end with gradual decrease in size of balls. As the charge rotates, differential centrifugal force causes the finer particles to move towards the discharge end. In this equipment, removal of discharge can be done from the side covers. So the mill operates simultaneously for size reduction as well as classification.

(b) **Continuous ball mills :** In the simple type of ball mill, it is not possible to remove fines without emptying the mill. Sieving of powder should be done separately. In continuously operating ball mills, series of chambers are separated by sieves of successively finer mesh size. The equipment is positioned under a small slope so that the powder can pass to the next chamber.

(c) **Vibrating ball mills :** In vibrating ball mills, the metallic cylinder is supported on a spring base and subjected to forced vibrations induced by electromagnetic means.

These have several advantages:

(1) Mill is free from rotating parts,
(2) It is easy to integrate the mills by classifiers and other ancillary system,
(3) Vibrating mill grinds at rates often as high as 20 to 30 times that of the conventional mills,
(4) Grinding efficiency is also high.

Fluid Energy Mill or Jet Mill or Micronizers or Ultrafine Grinders

Principle : Fluid energy mill operates on the principle of impact and attrition. In this equipment, the feedstock is suspended within a high velocity air stream. Milling takes place, because of high velocity collisions between the suspended particles.

Construction : The construction of a fluid energy mill is shown in Figure 3-10. Fluid energy mill consists of an elliptical pipe, which has a height of about 2 metres and diameter ranging from 20 to 200 mm. The mill surface may be made of either soft stainless steel or tough ceramics. Usually, mills are constructed such that the contact surfaces are merely linings, which can be removed or replaced, if excessively eroded after use.

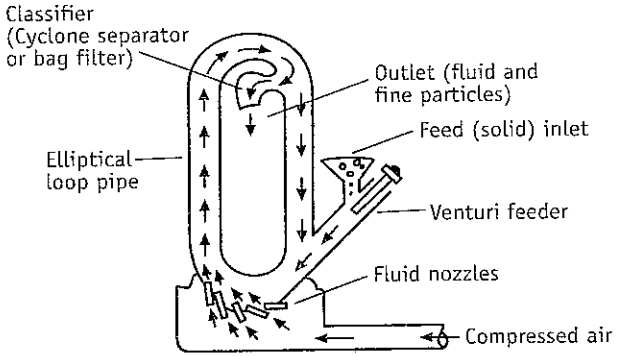


Figure 3-10. Fluid energy mill.

Grinding nozzles (usually two to six) may be placed tangential and/or opposed to the initial flow path of a powder. Normally, compressed air of 600 kilopascals to 1.0 megapascal is used. Inert gases can be used to minimize or eliminate the oxidation of susceptible compounds. Venturi feeder is provided in the path of the airflow. An outlet with a classifier (cyclone separator or bag filter) is fitted to allow the escape of air.

Working : Powder is introduced through the inlet of venturi. The air entering through the grinding nozzles transport the powder in the elliptical or circular track of the mill. In the turbulent stream of air, the suspended particles collide with each other and break. Thus, impact and attrition forces operate in size reduction. The resultant small particles (entraped by air) are carried to outlet and removed by cyclone separator or bag filters.

The coarser particles undergo re-circulation in the chamber on account of its own weight. These re-circulated particles collide again with new in-coming feed stock particles. The powder remains in the mill, until its size is reduced sufficiently. Later it leaves via the screens. Hence, fluid energy mill produces particles with narrow size distribution. Sometimes

the particles, which are entrapped by the drag of gas, leave the mill and carried out to a cyclone separator or bag collector.

Uses : Fluid energy mill is used to reduce the particle size of most of the drugs such as antibiotics and vitamins. When strict quality control is desirable for the purpose of better absorption (bioavailability), this mill is the preferred one. Moderately hard materials can be processed for size reduction.

Advantages : (1) It has no moving parts, hence, heat is not produced during milling. Therefore, heat-labile substances can be milled. E.g. sulphonamides, vitamins and antibiotics. Due to the expansion of gases under pressure cooling effect is produced during milling.

(2) It is a rapid and an efficient method for reducing powders to 30 μm or less.

(3) Since there is no wear of the mill, contamination is not possible.

Disadvantages : (1) Fluid energy mill is not suitable for milling of soft, tacky and fibrous materials.

(2) The equipment is expensive, because it needs additional accessories particularly fluid energy source and dust collection equipment.

Variants : *Centrifugal-impact pulverizer*—In centrifugal impact pulverizers, a rotor is spinned to induce high centrifugal force on the feed particles. The particles move towards the impactors, which are set at the periphery of the rotor. On striking these impactors, the material is further hurled against the outer casing where final reduction is achieved. The material is removed from the conical discharge at the bottom.

Particle size reduction in the range of 10 to 325 meshes can be obtained with this type of mill. Centrifugal impact pulverizers have been used for the size reduction of a variety of materials ranging from soft organic molecules to hard abrasive materials. It is also well suited for the size reduction of heat sensitive materials.

Colloid Mill

Principle : Colloid mill consists of two steel discs (stator and rotor) having very small clearance between them. One disc is rotating, while the other one is stationary. When the material is passed through these discs, they get sheared. Thus, coarse particles are broken down into small particles due to shear.

Construction : The construction of a colloid mill is shown in Figure 3-11. The colloid mill consists of high-speed rotor and stator with conical milling surface. The milling surfaces may be smooth surfaced or rough

surfaced. Rough surfaced mills are used for fibrous material because fibres tend to interlock and clog smooth surfaced mills. The clearance between rotor and stator can be adjusted from 0.05 to 0.75 mm. During milling, the heat generated may rise the temperature up to 40 °C. Hence, cold water circulation is provided to reduce the temperature as much as 20 °C. The discharge pipe is also connected to hopper, so that discharge can be recycled.

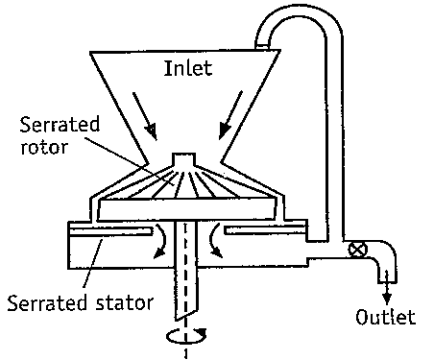


Figure 3-11. Colloid mill.

Working : Materials for the manufacture of suspensions and emulsions are placed in the hopper. Usually, the solids are pre-milled to prevent the damage of colloid mill. The solids are mixed with the liquid vehicle before introducing into the colloid mill. The dispersion flows down and adheres to the rotor. During the movement of rotor (3000 to 20000 rotations per minute), centrifugal force throws a part of the dispersion on to the stator. Depending on the clearance, the dispersion is sheared between rotor and stator. Thus, size reduction can be achieved. The milled liquid may be recycled. After achieving the desired size, the discharge is collected from the outlet in the periphery of the housing.

Normally, the size of milled particles may be smaller than the clearance, because of the force of high shear. In emulsification, a clearance of 75 μm may produce dispersion with an average particle size of 3 μm.

The capacities of colloid mills range from 2 to 3 L/min for small mills to 440 L/min for the larger mills.

Uses : Colloid mill is used for preparing colloidal dispersions, suspensions, emulsions and ointments. Particle size as small as 3 μm can be obtained. Fibrous material can be milled using rough surfaced rotor and stator.

Advantage : Colloid mill can be sterilised. So it can be used in the production of sterile products.

Disadvantages : (1) Colloid mill tends to incorporate air into the finished product. Therefore, the product should be allowed to rest for some time for deaeration.

(2) Heat is generated during milling. Hence, water circulation facility around the milling chamber has to be provided.

(3) Colloid mill is not useful for dry milling.

Edge Runner Mill

Principle : The size reduction is done by crushing (compression) due to heavy weight of stones. Shearing force is also involved during the movement of the stones.

Construction : The construction of an edge runner mill is shown in Figure 3-12. It consists of two heavy rollers and may weigh several tons. The rollers move on a bed, which is made of stone or granite. Each roller has a central shaft and revolve on its axis. Further, the rollers are mounted on a horizontal shaft and move around the bed.

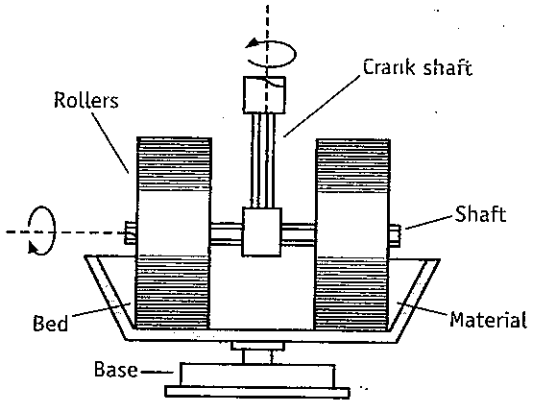


Figure 3-12. Edge runner mill.

Working : The material to be ground is placed on the bed. With the help of a scrapper, it is kept in the path of the stone wheel. The stones revolve on their common axis, and at the same time travel round the shallow stone bed. The outer part of the wheel has to travel a greater distance than the inner, so that size reduction is achieved by shearing as well as crushing. The material is ground for a definite period. The powder is collected and passed through a sieve to get powder of the required size. It is a batch process.

Uses : Edge runner mill is used for grinding tough materials to fine powder. It is still used for plant-based products, while more sophisticated mills are used for chemicals and drugs.

Advantages : Edge runner mill does not require attention during operation.

Disadvantages : (1) Edge runner mill occupies more space than other commonly used mills.

(2) Contamination of the product with roller material is possible.

(3) The milling process is time consuming.

(4) It is not used for sticky materials.

(5) Energy consumption is quite high.

End Runner Mill

Principle : Size reduction is done by crushing (compression) due to heavy weight of steel pestle. Shearing stress is also involved during the movement of mortar and pestle.

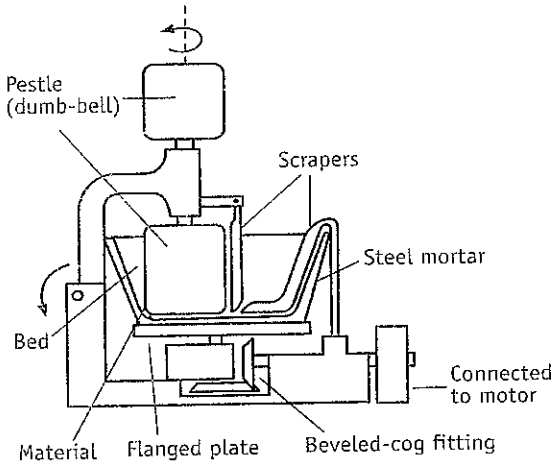


Figure 3-13. End runner mill.

Construction : The construction of an end runner mill is shown in Figure 3-13. It is considered as a mechanical mortar and pestle. It consists of a steel mortar, which is fixed to a flanged plate. Underneath the flanged plate, a bevelled cog fitting is attached to a horizontal shaft bearing a pulley. Hence, the plate with mortar can be rotated at a high speed.

The pestle is dumb-bell shaped so that balancing and efficient grinding by its weight can be achieved. The bottom of pestle is flat rather than round. The pestle carries an arm, which is hinged. By this arrangement, the pestle can be raised from the mortar to facilitate emptying and cleaning. The narrow central portion of the pestle is longer than the band of the arm around it. Hence, pestle can rise and fall over the material in the mortar.

Working : The material to be ground is placed in the mortar. The scraper puts the material in the path of the pestle. The mortar revolves at a high speed. The pestle is placed in the mortar. The rotating mortar causes the pestle to revolve. During this process, size reduction is achieved by shearing as well as crushing. The material is collected and passed through a sieve to get the powder of desired size.

Uses : End runner mill is suitable for fine grinding.

Disadvantage : End runner mill is not suitable for drugs, which are in unbroken or slightly broken conditions.

Pin Mill

Principle : Pin mill achieves size reduction primarily on the principle of impact, but partly by attrition. The material passes through the clearance of pins attached to the oppositely rotating steel plates. These are a class of high speed mills.

Construction : The construction of a pin mill is shown in Fig. 3-14. It consists of two vertical steel plates with horizontal projections (pins) arranged in concentric circles on opposing faces. The circles alternate so that the pins pass each other on rotation. The pins are more closely spaced towards the periphery of the plates. These two plates move in close spaces so that the pins intermesh. This unit is often attached with a vane classifier, which facilitates the return of coarse particles for further size reduction.

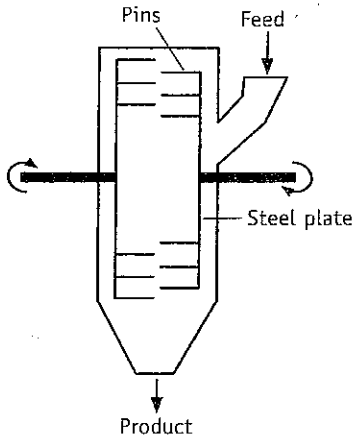


Figure 3-14. Pin mill.

Working : The steel plates are allowed to rotate. The feed material is placed into the hopper, which then flows down to the centre of the steel plates. When plates are in continuous motion at high speed, centrifugal action is propelled, so that a large amount of material is thrown towards the periphery. The material passes through the pins. The rotating pins beat the material to yield small particles. Size reduction is provided by impact and attrition mechanisms. The milling is more at the periphery, because pins are close to each other. From the periphery, the material flows to a separator, so that any grade of fineness can be achieved. The coarse particles return to the mill for further size reduction.

Uses : Damp solids as well as dry solids can be handled using the pin mill. Oily materials (full-fat cooked soya meal), soft and non abrasive material can be size reduced.

Advantages : Screens and gratings are absent, thereby clog-free action is achieved. Low milling temperature permits the size reduction of heat sensitive material. The fineness of grinding can be varied by the use of discs with different dispositions of pins. These mills are available at different capacities, 20 to 4000 kg/h and at the fineness from 2.0 to 2.0 μm.

Variants : Horizontal rotating pins type mill is available and also works at high speeds, however, the principle remains the same. E.g. Mikro-ACM pulverizer and Killoplex mill.

In summary, several size reduction equipment are described. Some general characteristics of various types of mills are given in Table 3-1.

TABLE 3-1
General Characteristics of Various Types of Mills

Name of the mill	*Mode of action*	*Product size*	*Uses*	*Not used for*
Cutter mill	Cutting	20 to 80 mesh	Fibrous, (animal and crude vegetable drug)	Friable material
Roller mill	Compression	20 to 200 mesh	Soft material	Abrasive material
Hammer mill	Impact	4 to 325 mesh	All most all drugs	Abrasive material
Ball mill	Attrition & impact	20 to 200 mesh	Brittle drugs	Soft material
Fluid energy mill	Attrition & impact	1 to 30 mm	Moderately hard and friable material	Soft and sticky material
Edge runner mill	Crushing & shearing	20 to 80 mesh	Almost all drugs	Sticky material
End runner mill	Crushing & shearing	20 to 80 mesh	Almost all drugs	Sticky material
Colloid mill	Shearing	3-75 μm	Almost all drugs	Dry milling
Pin mill	Impact	2 to 2 mm	Damp solid, dry solid	—

Open Circuit and Closed Circuit Mill

The size reduction process may be achieved in open circuit or closed circuit conditions.

An *open-circuit mill* is one in which milling operation is carried out in one attempt, i.e. by passing the feed material through the mill to obtain the desired size.

A *closed-circuit mill* is one in which the discharge from the milling process is passed through a size separation device or classifier, and the oversize particles are returned to the grinding chamber for further size reduction.

The principle of closed circuit grinding is widely used in the pharmaceutical industry. It has the advantages:

(a) It provides fine and ultra-fine sizes.
(b) It eliminates dust.
(c) It eliminates overheating.
(d) It produces a product that is free from oversize or undersize.

A closed circuit with an air classifier is shown in Figure 3-15. In this type, size reduction is combined with size classification. The working of hammer mill is illustrated in Figure 3-15. The coarse material returning to the mill by a classifier is known as circulating load.

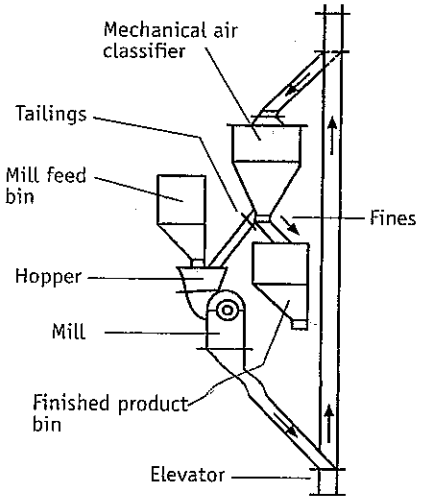


Figure 3-15. Closed circuit milling system with hammer mill.

Dry and Wet Grinding

The use of a product and subsequent steps mainly decide the type of equipment used. In the preparation of colloidal dispersions, suspensions, emulsions and ointments, wet grinding offers advantages. In their production, wet grinding has become an integral part of the processing. For example, mill can be also used as mixing equipment. Triple roller mill,

colloid mill are used for such a purpose. In such situations, producing an excellent dispersion is the primary objective and size reduction is of secondary importance.

Wet grinding is preferred when dry grinding produces aggregation of particles. In practice, it is found that finer size can be achieved by wet grinding than by dry grinding. Wet grinding is used in the production of flocculated suspensions. In wet grinding, surfactants are added to attain particle size of 0.5 μm. The **advantages** of wet grinding are:

(1) it eliminates the dust hazards,
(2) wet grinding is usually done at low speed, therefore, it consumes less power (energy),
(3) increased milling capacity, low energy consumption,
(4) easier material handing,
(5) grinding aids can be incorporated.
(6) The material contains moisture (5 and 50 %) and forms cake. The material does not flow. Dry milling is not suitable and proves low efficient.
(7) The product does not require drying step in downstream process.

The **disadvantage** is the increased wear of the grinding medium.

Colloid and ball mills are best suited for wet grinding. If the product undergoes physical or chemical changes in water, dry milling is recommended. The fineness is limited to 100 μm. All the mills reported earlier except colloid mill can be used for dry grinding.

Comment 3-4. In a hammer mill, the size of particles is far less than the mesh size of the screen. How is it possible?

Comment 3-5. Fluid energy mill is better equipment than hammer mill, for the size reduction of thermo-labile substances. Substantiate.

Comment 3-6. Why is ball mill not suitable for size reduction of fibrous material?

Comment 3-7. How is it possible to prevent heat generation in a colloid mill?

Comment 3-8. Why is it essential to include a screen in the size reduction equipment?

Comment 3-9. Size reduction equipment can also be used as mixing equipment. Explain.

SELECTION OF A MILL

The selection of a particular equipment for size reduction depends on a number factors. These are related to the feed, milled product, safety and economics.

Factors Related to the Nature of Raw Materials

The properties of a solid determine its ability to resist size reduction and influence the choice of equipment used for milling. Some physical properties of the feed are as follows.

Hard materials : Iodine and pumice are hard and abrasive. In general, hard materials are most difficult to comminute. For iodine, hammer mill or fluid energy mill is used. Size reduction process of such materials can lead to abrasive wear of milling parts, which then cause contamination.

Fibrous materials : Glycyrrhiza, rauwolfia, ginger etc. are fibrous in nature and cannot be crushed by pressure or impact. Fibrous materials are tough in nature. They must be teared by a cutter. Nux vomica and ipecacuanha are processed in two stages to get fine powders.

Friable materials : Sucrose and dried filter-cake are friable and tend to fracture along well-defined planes. Brittle substances can be easily converted to smaller particles. Such materials are milled by the mechanisms such as attrition, impact or pressure. For example, sugar is milled using hammer and fluid energy mills.

Elastic materials : Synthetic gums, waxes and resins become soft and plastic during milling. These low-melting substances should be mill chilled before milling. Such materials are milled using hammer mill, colloid mill or fluid energy mill.

Hygroscopic materials : Substances such as potassium carbonate absorb moisture rapidly. This wet mass sticks and clogs the mill. They are prepared in a closed system such as porcelain ball mill.

Structural changes : During milling (in a ball mill) to a fine state produces structural changes, such as changes in the crystalline form (e.g. calcium carbonate), polymeric changes (e.g. barbiturates), liberation of water from hydrate (e.g. sodium sulphate, Na_2SO_4, $10H_2O$) and causing clogging of the mill. Such changes affect the solubility and other physicochemical properties, which in turn influence the therapeutic values.

Melting point : Solids with low melting points often become soft and melt owing to the heat generated during milling. Such materials are chilled before milling. Grinding to a fine state of subdivision may cause caking of the product, if the softening point exceeds. In such cases, the materials are either chilled before milling or cool the mill during milling. Waxy solids can be successfully ground with dry ice and low temperature also confers brittle characteristics.

Thermolability : Certain substances undergo degradation reactions such as hydrolysis and oxidation due to the presence of moisture and atmospheric oxygen. Such reactions proceed faster owing to the heat produced

during milling. These should be milled in a closed system with an inert atmosphere of carbon dioxide or nitrogen. Vitamins and antibiotics are milled using fluid energy or ball mills.

Flammability : Almost any fine dust, such as dextrin, starch and sulphur, is a potential explosive mixture under certain conditions. All electrical switches should be explosive proof and the mill should be properly grounded (earthed).

Particle size of the feed : For a mill to operate satisfactorily, the feed should be of proper size. For example, pretreatment of fibrous materials with high pressure rollers or cutters facilitates further comminution.

Moisture content : Presence of more than 5 % water hinders the milling process and produces a sticky mass. The effect is more pronounced, when the concentration of water is more. In general, materials with moisture content below 5 % are suitable for dry grinding and from 5 to 50 % are suitable for wet grinding.

Pretreatment : For the mill to operate satisfactorily, the feed should be of a proper size and enter the equipment at a fairly uniform rate. Therefore, a pretreatment step should be included. For example, fibrous material should be treated with cutter or roller, which can facilitate further comminution.

Factors Related to the Nature of Finished Product

The nature of finished (milled) product also influences the selection of the equipment.

Particle size : If extreme size control is necessary, it may be essential to recycle the larger particles. This can be achieved by screening the discharge material and returning the over size particles for a second time milling. Moderately coarse or coarse powders with a minimum of fine powder are easily obtained using a high-speed impact mill. For example, cascara, liquorice, belladonna leaves and roots are easily broken down by impact mill.

For example, particle size of griseofulvin is critical in the production. Similarly the particle size is also critical in the suspension of penicillin G procaine for intra-muscular injection to facilitate its syringeability.

Ease of sterilisation : When preparations are intended for parenteral and ophthalmic uses, size reduction should be conducted in a sterile environment. The equipment should be sterilisable. Ball mill and fluid energy mill are suitable for this purpose.

Contamination of milled materials : In case of potent drugs and low dose products, contamination of the product should be avoided. Use of

equipment that is free from wearing of mill parts is preferred. Fluid energy mill is suitable for this purpose.

In addition to the end use of a product, subsequent processing steps mainly determine the choice of wet or dry milling. In the preparation of colloidal dispersions, suspensions, emulsions and ointments, wet grinding offers advantages in terms of size reduction of materials, elimination of dust hazards. Thus, wet grinding has become an integral part of the processing of the above dosage forms. The same mill can also be used as mixing equipment. E.g. triple roller mill and colloid mill.

Factors Related to Safety

The factors related to safety are explosivity, irritability and toxicity. During milling, fine dust of drug arises which may become flammable under certain conditions. Dry grinding produces the hazard of dust. Explosion hazards of non-metallic materials, such as sulphur, starch and wood floor, are often appreciable. Metal powders pose a hazard because of their flammability. The useful precautions are:

(a) isolate the mill and make it dust proof.
(b) use of non-sparking material of construction.

Stainless steel has less sparking tendency than ordinary steel or forging.

Factors Related to the Economy

Cost, power consumption, space occupied and labour costs are some of the economic factors that determine the selection of a mill.

Cost : In processing of ore, size reduction constitutes a major portion of costs. On the other hand, drug materials are expensive and processed in relatively small quantities. The contribution of grinding to the total cost is smaller. Hence, the choice of machine is usually made on technological rather than economic grounds. Where the particle size control is not critical, the cost decides the type of equipment. In general, the cost of the size reduction increases, as the particle size decreases. Therefore, it is economically undesirable to reduce the particle size to a finer degree than necessary.

THEORIES OF COMMINUTION

Mechanical Behaviour of Solids

When various modes of stress are applied on a powder, the particles get strained. This stress-strain relationship is shown in Figure 3-16.

- In Figure 3-16, the initial linear portion is defined by Hooke's law. It states that stress is proportional to strain. The slope of linear portion represents *Young's modulus*. It expresses the stiffness or softness in mega-pascals.

- If the force of impact (stress) does not exceed the elastic limit (region of Hooke's law), the material is reversibly deformed. When the force is removed, the particle returns to original condition. The elastic limit is known as *yield value*. The stress energy in the deformed particle appears as heat. Example is plastic material such as polymer.

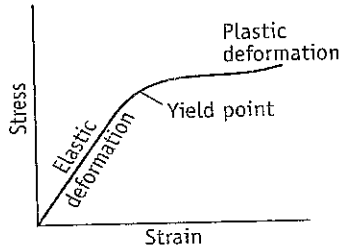


Figure 3-16.
Stress-strain curve for a solid.

- The stress-strain curve starts becoming nonlinear at the yield point. This is a measure of the resistance to permanent deformation.
- Beyond the yield point, the region represents irreversible plastic deformation. If plastic deformation is observed for longer period, the material is classified as ductile.
- The area under the curve represents the fracture toughness (or modulus of toughness). This is an approximate measure of the impact strength of the material. Fracture is explained in terms of cracks and flaws naturally present in the material. This process occurs suddenly. Fracture of a particle can be obtained when the force exceeds the elastic limit.

Theories of Size Reduction

(1) According to Griffith theory, all solids contain flaws and microscopic cracks. A *flaw* is any structural weakness that may develop into a crack under strain. The weakest flaw in a particle determines its fracture strength. It controls the number of particles produced by fracture. The particles with the weakest flaw fractures most easily and produce largest possible pieces. In the next step, another weakest flaw fractures. This process continues until all flaws are fractured. The particle size produced in this process may not be the desirable one. However, Griffith theory is simple and explains the size reduction process reasonably.

According to Griffith theory, the amount of force to be applied depends on the crack length and focus of stress at the atomic bond of the crack apex. This relationship may be mathematically expressed as:

$$T = \sqrt{\frac{Y\varepsilon}{c}} \qquad \ldots(1)$$

where T = tensile strength, MPa
Y = Young's modulus, MPa

ε = surface energy of the wall of crack, J/m^2
c = critical crack path required for fracture, m

A linear relationship (equation 1) between the square of tensile strength of minerals and the critical height for drop weight impact suggests that the square of tensile strength is a useful criterion of impact fracture.

(2) If flaws are not present in a particle, the force of milling produces new flaws. The useful work in milling is proportional to the length of new crack formed. The mechanism of creating new flaws in a particle is as follows.

The strength of most materials is greater in compression than in tension. It is therefore unfortunate that technical difficulties prevent the direct use of tensile stresses. The compressive stresses commonly used in comminuition equipment do not cause failure directly, but generate, by distortion, sufficient tensile or shear stress to form a crack tip in a region away from the point of primary stress application. The rate of stress application is so high that the limiting stress energy may exceed several times.

Usually, the surface of particles is irregular. The applied force is initially taken on the high portion of the surface. As a result, high stress and increased temperature may be set up locally in the particle. The bonds at this place become weak, which may be responsible for creating flaws. The particle further absorbs applied strain energy and is deformed. The strain energy required to extend the crack to fracture is proportional to the length of the crack formed. This energy is supplied by the flow of the residual strain energy to the crack.

(3) Not all materials exhibit this type of brittle behaviour. They resist fracture even at much larger stresses, because these are tougher. They undergo plastic flow, which allows strain energy relaxation without crack propagation. When plastic flow occurs, atoms or molecules slip over one another and this process of deformation requires energy.

ENERGY OF COMMINUTION

Size reduction begins with the opening of small flaws that are initially present. Based on the probability, larger particles may have numerous flaws and readily fracture when compared to smaller particles with fewer flaws. The supplied energy is used to:

- Increase new surface area from flaws.
- Initiate flaws or cracks in the particle.

This phenomenon is observed generally in fine grinding.

Most efficient mills utilise less than 1 % of the energy input to fracture particles or create new surfaces. The rest of energy is dissipated in:

1. Elastic deformation of unfractured particles.

2. Transport of material within the milling chamber.
3. Friction between the particles.
4. Friction between the particles and mill.
5. Heat.
6. Vibration and noise.

Energy input and utilisation are important factors to estimate the efficiency of a mill for a given material. The mill efficiency can be determined through experimentation. The energy consumed and particle reduction achieved is compared to the values obtained under free crushing conditions. The ratio of energy requirement to generate new surfaces is a parameter used to evaluate the mill efficiency. It is necessary initially to qualify whether a particular mill is meant for intended purpose or not. Otherwise the calculated mill efficiency (size reduction ratio) becomes erratic. It is minimal at optima conditions.

- If grinding is desirable for obtaining fine powder, the ratio is increased.
- The fluid energy mill has a size reduction ratio of up to 400, which is exceptional.
- Normally, low retention times are sufficient in free crushing machines.
- If the speed of the mill is low, longer time of milling is necessary.
- Over-grinding (excessive fines or undersize powder) should be avoided.
- As the milling time increases, the effectiveness of grinding reduces progressively.

A number of theories have been proposed to establish a relationship between energy input and the degree of size reduction produced.

The energy required to reduce the size of the particles is inversely proportional to the size raised to some power. This may be expressed mathematically as;

$$\frac{dE}{dD} = \frac{-C}{D^n} \qquad ...(2)$$

where E = amount of energy (work done) required to produce a change, kW·h
D = size of unit mass, μm
C = constant, W·h
n = constant

Equation (2) may be written (when $n = 1$) as:

$$E = C \ln\left(\frac{d_i}{d_n}\right) \qquad ...(3)$$

where d_i = size of the feed, μm
d_n = size of the product, μm

In equation (3), (d_i/d_n) is known as reduction ratio. The usefulness of equation (3) is that it satisfies various laws proposed. These are:

For $n = 1.0$, equation (3) becomes Kick's law
For $n = 1.5$, equation (3) becomes Bond's law
For $n = 2.0$, equation (3) becomes Rittinger's law

Rittinger's Theory

According to the Rittinger's hypothesis, energy, E required for size reduction of unit mass is directly proportional to the new surface area produced. It is expressed as:

$$E = K_R\left(\frac{1}{d_n} - \frac{1}{d_i}\right) \qquad ...(4)$$

where d_i = diameter of particle, μm
d_n = new diameter of particle, μm
K_R = Rittinger's constant, energy per unit area, kW·h./μm^3
E = amount of energy (work done), kW·h

The constant K_R depends on the grinding unit employed. The energy is consumed to enlarge the surface area of one unit. It is mostly applicable to brittle materials undergoing fine milling. Rittinger's theory ignores particle deformation before fracture.

Bond's Theory

According to the Bond's theory, the energy used in crack propagation is proportional to the new crack length produced. Three principles are proposed.

1. Any divided material must have a positive energy register. This can be zero when the particle size becomes infinity.

$$\text{Input energy } (E) = \begin{matrix}\text{energy register of product} \\ - \text{ energy register of the feed}\end{matrix}$$

   As the particle size decreases, the energy associated with the powder increases. In other words, energy register is inversely proportional to the particle size.
2. For a stated weight of homogeneous materials, the total work (useful for the size reduction) is inversely proportional to the square root of the diameter of the particles of product.
3. The breakage of the material is determined by the flaw structure.

Bond's theory states that the energy used for deforming or fracturing a set of particles of equivalent shape is proportional to the change in particles dimensions. According to Bond's theory, the equation can be written as:

$$E = 2\,K_B \left(\frac{1}{\sqrt{d_n}} - \frac{1}{\sqrt{d_i}} \right) \qquad ...(5)$$

where K_B = Bond's work index, energy per unit mass, kW·h·√μm

Bond's work index is the work required to reduce a unit weight from a theoretical infinite size to 80 % passing 100 μm. According to this theory, the energy used in crack propagation is proportional to the new crack length produced. This law is useful for rough mill sizing. The work index is useful for comparing the efficiency of milling operations.

Kick's Theory

According to the Kick's theory, the energy used in deforming or fracturing a set of particles of equivalent shape is proportional to the ratio of the size changes. It may be expressed as:

$$E = K_K \ln \frac{d_i}{d_n} \qquad ...(6)$$

where K_K = Kick's constant, energy per unit mass, kW·h

The Kick's proposal was developed on a stress-strain diagram for cubes under compression. It assumes that the material has flaws distributed throughout its internal structure. For crushing (compression) of large particles, Kick's equation (equation 6) is more useful. It is applicable to elastic materials undergoing deformation and/or brittle fracture.

The energy requirement does not dependent on the initial particle size, but depends on size reduction ratio. The theory assumes that the resistance to crushing does not change with particle size. The energy requirements predicted by Kicks are lower than that of the Rittinger's. Equations (1 to 6) apply precisely only under the condition that all the energy is transferred into surface energy.

Size reduction of a material is alone not sufficient to obtain powder of desired size. It is followed by separation. Several equipment described earlier also include sieves or screens as integral parts. However, size separation is discussed separately in the following chapter.

Comment 3-10. A single theory is not sufficient to explain milling of all types of the particles. Explain.

Summary

Size reduction process is also termed as comminution, diminution, pulverization or milling. It is used to reduce the size of large solids, either vegetable or chemical origin, into small sizes, either coarse or fine particles. Many pharmaceutical powders are *polydisperse* though monosize are preferred. The strength of materials is explained in terms of various types of flaws, cracks and cleavage. Size reduction offers several applications: the promising one is the enhanced drug dissolution and bioavailability. During size reduction, the flaws propagate into cracks. Simultaneously new flaws are also created and so on size reduction continues. The net result is creating new surfaces, increasing the surface area of the powder by reducing the particle size. Since the nature of materials are diverse, several modes of stress is applied, namely cutting, compression, impact and attrition. In several situations, all the modes operate simultaneously. Numerous types of size-reduction equipment are developed to handle materials of different properties. It is essential to know the properties of the materials before commencement of the size reduction. The hardness and fibrous brittleness are a few parameters that govern the size reduction. All equipment provides the necessary energy to break the bonds that are holding the particle interact (in the feed). The materials obtained from different mills exhibit distinct properties. For example, the powder produced by a ball mill differs from those produced by a hammer mill. The equipment available for size reduction are: cutter mill, roller mill, ball mill, fluid energy mill, edge runner mill, end runner mill, hammer mill, pin mill and colloid mill. In general, size reduction equipment consists of a three basic components namely feed introduction, milling chamber and receiving chute. The factors namely hardness, stickiness, slipperiness, moisture content, melting or softening point, abrasiveness, ratio of feed size to product size, etc. affect the selection of size reduction equipment. When stress is applied on the powder, the particle gets strained. The stress-stain curve is characterized by elastic deformation, yield point, plastic deformation and brittle fracture. Based on these trends, several theories are proposed to explain the size reduction process. The most efficient mills utilize less than 1 % of the energy input to fracture. The rest of the energy is dissipated into heat, friction losses, insufficiency of transmission, etc. The energy required to reduce the size of particle is inversely proportional to the size raised to the power n. The size reduction process is expressed as reduction ratio. The change observed after size reduction may be expressed as: increased surface area (Rittinger's theory), lower particle size (Bond theory and Kick's theory). These theories also have basis from mechanisms of size reduction. For example, Rittinger's theory describes the fracture, while Bond theory explains the crack propagation and crack creation. Kick's theory explains the deforming or fracture. Further, theories have bearing on the modes of size reduction. Rittinger's theory describes impact, Bond theory considers cutting and Kick's theory explains compression.

Glossary of Symbols

C = Constant or coefficient.
c = Critical crack path required for fracture, m.
D = Size of unit mass, μm.
E = Amount of energy required to produce a change in unit mass, kW·h.
d_i = Size of the feed or initial diameter of particles, μm.
d_n = Size of the product or new diameter of the particles, μm.
ε = Surface energy of the wall of crack, J/m^2.
K_B = Bond's work index, energy per unit mass, $kW \cdot h \cdot \sqrt{\mu m}$.
K_K = Kick's constant, kW·h.
K_R = Rittinger's constant, $kW \cdot h/\mu m^2$.
n = Constant.
S_i = Initial specific surface area, $\mu m^2/\mu m^3$.
S_n = New specific surface area, $\mu m^2/\mu m^3$.
T = Tensile strength, MPa.
Y = Young's modulus, MPa.

QUESTION BANK

Each question carries one mark

Note : Encircle the alphabet which corresponds to the single best response.

1. Size reduction CANNOT be obtained by one of the following methods.
   A. Flocculation B. Mechanical
   C. Physical D. Precipitation
2. Which is the mill preferred for wet grinding?
   A. Colloid mill B. Hammer mill
   C. Roller mill D. Rotary cutter mill
3. Size reduction of potent materials is necessary for one of the following quality control parameters, in formulation of dosage forms.
   A. Content uniformity B. Friability
   C. Hardness D. Poor mixing
4. Size reduction of materials has one of the following disadvantages.
   A. High degradation B. High dissolution
   C. High flow of materials D. High surface area
5. Which one of the following sequences is involved in the mechanisms of size reduction?
   A. Chipping and cracks
   B. Chipping and flaws
   C. Chipping, flaws and cracks
   D. Chipping, flaws, cracks and cleavage
6. Which one of the following is NOT a mode of stress in size reduction?
   A. Classification B. Collision
   C. Compression D. Cutting
7. Which one of the following parameters of finished product does NOT influence the selection of size reduction equipment?
   A. Porosity B. Shape
   C. Surface roughness D. True density
8. Which are the modes observed in a ball mill for size reduction?
   A. Attrition and cutting B. Compression and impact
   C. Cutting and compression D. Impact and attrition
9. Which mill includes a screen as an integral part of the size reduction?
   A. Ball mill B. Colloid mill
   C. Edge runner mill D. Hammer mill
10. Which one of the following is NOT TRUE in case of construction of hammer mill?
    A. Hammers are flat or sharp edges
    B. Hammers are rigid or swing type
    C. Metal sheet with holes or slots
    D. Woven type of screen
11. Clearance between the stator and rotor is critical factor in one of the following size reduction mills.
    A. Colloid mill B. Fluid energy mill
    C. Hammer mill D. Rotary cutter mill
12. Which one of these is NOT a facility in colloid mill?
    A. Clearance between stator and rotor
    B. Dry grinding of feed
    C. Recirculation of milled product
    D. Water jacket for reducing the heat
13. If a given material is fibrous in nature, which mill is preferred?
    A. Ball mill B. Colloid mill
    C. Fluid energy mill D. Rotary cutter mill
14. The sterile product CANNOT be obtained by one of the following mills.
    A. Colloid mill B. Cutter mill
    C. Fluid energy mill D. Roller mill
15. Which principle operates in the hammer mill?
    A. Attrition B. Crushing
    C. Cutting D. Impact

16. In which equipment, the feed material is suspended within high velocity of air stream?
    A. Edge runner mill
    B. Pebble mill
    C. Rotary cutter mill
    D. Ultra-fine grinder
17. Which one of the following is NOT a size reduction process?
    A. Clarification
    B. Comminution
    C. Diminution
    D. Pulverization
18. Oil seed can be reduced in size using one of the following mills?
    A. Ball mill
    B. Fluidised energy mill
    C. Hammer mill
    D. Roller mill
19. Choose the theory that explains the size reduction of large particles by compression modes.
    A. Bond's theory
    B. Griffith theory
    C. Kick's theory
    D. Rittinger's theory
20. Choose the mill that does NOT involve shearing mechanism for size reduction.
    A. Colloid mill
    B. Edge runner mill
    C. End runner mill
    D. Hammer mill
21. One of the following is NOT associated with fluid energy mill.
    A. Consumes less energy
    B. Produces more fines
    C. Produces cooling
    D. Promotes contamination
22. Which one of the following is the mode(s) for size reduction by fluid energy mill?
    A. Attrition and cutting
    B. Attrition and compression
    C. Impact and attrition
    D. Impact and compression
23. Continued milling causes size enlargement by one of the causes.
    A. Diameter is less than 5 μm
    B. High cohesive forces
    C. Increased surface charge
    D. Spherical shape
24. In particle size reduction, one of the following statements is *always* true.
    A. Decreasing surface area
    B. Increasing the dust
    C. Enhancing of high energy molecules
    D. Producing the heat
25. Milling of drug powder does NOT produce one of the following.
    A. Degrades the thermolabile drugs
    B. Increases the dissolution rate
    C. Promotes the changes in polymorphic forms
    D. Reduces the particle aggregation
26. Which one the following is NOT an application of size reduction of particles.

    A. Decreasing the sedimentation in suspensions
    B. Improving percutaneous absorption from ointments
    C. Lowering the solubility of more soluble drugs
    D. Promoting lubricant function in compression
27. What is the operating mode of size reduction in a roller mill?
    A. Attrition
    B. Compression
    C. Impact
    D. Tearing
28. Which of the following is a mechanism of size reduction?
    A. Cutting
    B. Hardness
    C. Pulverization
    D. Toughness

Each question carries 2 marks

1. Screen type of sieves gives more fine powder than the wire woven sieves. Why?
2. Size reduction of vegetable matter is essential for the extraction of crude drugs. Explain.
3. It is difficult to obtain uniform sized product during milling without the use of sieves. Why?
4. When ball mill is used, size reduction is not obtained. Under what condition size reduction is not effective.
5. How do you prevent the problems of sticking and clogging of sieves in the size reduction?
6. List special precautions to be taken while thermolabile substances are subjected to size reduction process.
7. The powder must contain fewer amounts of fines when it is meant for percolation process of extraction. Why?
8. What are the advantages of swinging type of hammer compared to rigid hammers?
9. Powders of same particle size that are obtained by different equipment have same physicochemical characteristics. True or false. Justify.
10. List the areas in which size reduction equipment is used in tablet production.
11. A large number of size reduction equipment is available currently. Why do we require so many types of mills?
12. The classical equipment mortar and pestle uses the mechanism of impact in size reduction. True or False. Explain.
13. Fluid energy mill is meant for wet grinding. True or false. Explain.
14. Reducing the size of the particles to fines leads to particle aggregation. True or false. Explain.
15. How does stickiness affect the process of size reduction?
16. How does the presence of moisture interfere with the process of size reduction?
17. Differentiate the mechanisms, attrition and impact in size reduction.

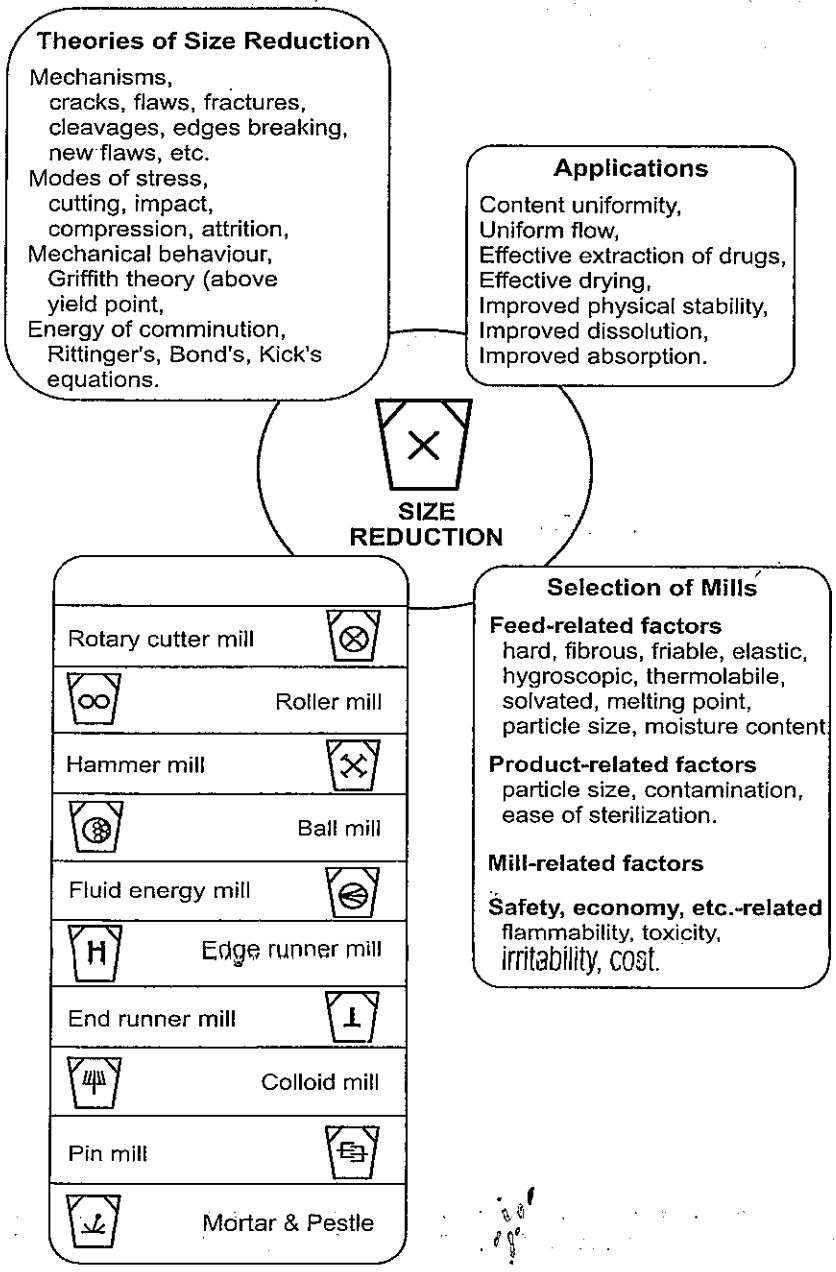
18. Differentiate dry and wet grinding.
19. Fine particles tend to undergo particle aggregation. Explain.
20. Why does wet grinding give finer sized powder than dry grinding?
21. Describe the conditions that favour the use of dry milling.
22. The strength of real materials in real terms is always less than the theoretical strength. Why?
23. It is difficult to grind the material progressively and continuously. Explain.
24. Why is screen not used in fluidized energy mill?
25. Why is narrow size distribution achieved in fluid energy mill, though screen is not used.

Each question carries 5 marks

1. Describe five factors that influence the selection of milling equipment for size reduction.
2. Explain with the help of a diagram the construction and working of a ball mill.
3. Explain with the help of diagram the construction and working of a hammer mill.
4. Describe the mechanisms of size reduction with suitable examples of equipment.
5. What is ultra-fine grinder? Explain the concept of ultra-fine grinding.
6. Describe 'micronizer'. Describe aseptic grinding process of antibiotics.
7. List the laws governing size reduction. What is work index?
8. How is size reduction affected in ultra-fine grinders? Describe the mechanism.
9. How is energy utilised in size reduction accounted for?
10. Explain the critical quality attributes for milling with an appropriate process parameters and material attributes.

Each question carries 10 marks

1. Explain the factors related to feed-material influencing size reduction.
2. Describe the construction, working, advantages and disadvantages of fluid energy mill.
3. Describe the milling equipment with the help of a neat diagram that uses the principle of shear and impact.
4. Explain the theories related to the size reduction of a powder.
5. Explain the advantages and disadvantages of size reduction process.
6. State and explain the laws governing size reduction.
7. Describe the mechanisms and modes of size reduction of solid drugs.



MIND MAP OF SIZE REDUCTION OPERATION

CHAPTER 4

Size Separation

Official Standards for Powders
Sieves
Modes of Motion in Size Separation
Testing of Powder — Sieve Analysis
Equipment for Size Separation
Settling Behaviour of Solids — Methods
Elutriation Methods
Selection of Size Separation Equipment

LEARNING OBJECTIVES

After reading this chapter, the reader should be able to:

- Understand the importance of grading of powders, sieves and details of their standards along with applications.
- Explain the testing of powder with standard equipment.
- Explain the design of size separation equipment along with working and uses at the industry level.
- Explain the principles of sedimentation and elutriation in size separation with applications.

Size separation is a unit operation that involves the separation of a mixture of various sizes of particles into two or more portions by means of screening surfaces.

Size separation is also known as *sieving*, *sifting*, *classifying* or *screening*. This technique is based on physical differences among the particles such as size, shape and density.

Size reduction of a solid material never gives particles of same size, but gives particles of varying sizes, i.e. distributes in different sizes. These materials must be subjected to a separation technique to obtain narrow size ranges. As far as possible size separation is included as an integral part of the size reduction process. When particle size distribution is to be controlled for the official specifications, size separation assumes greater importance and has to be handled independent of the size reduction.

Screening is a method of separating particles according to size alone. Particles can be separated into individual sizes using sieves. The final portion consists of a more uniform size. The material that remains on the given screening surface is known as oversize or plus material. The material passing through the screening surface is known as undersize or minus material.

Applications

Size separation of solids has important applications.

1. As a method to determine particle size and size distribution, which are useful in the production of tablets and capsules.
2. As a quality control tool for the analysis of raw materials such as griseofulvin and aspirin.
3. To test the efficiency of a size reduction equipment or process.
4. To optimise the process conditions namely method of agitation, time of screening, feed rate, etc.
5. To recover valuable products or byproducts.
6. To prevent environmental pollution.

OFFICIAL STANDARDS FOR POWDERS

In general, powders are vaguely described as coarse and fine powders. However, it is essential to identify with some guiding specifications.

Indian Pharmacopœia has prescribed standards for powders for pharmaceutical purposes. Accordingly, degree of coarseness or fineness is ex-

TABLE 4-1
Grades of Powders and Sieve Number alongwith Nominal Aperture Size as per IP

Sl. No.	*Grade of powder*	*Sieve through which all particles must pass*	*Nominal mesh aperture size*	*Sieve through which 40 % particles pass*	*Nominal mesh aperture size*
1	Coarse powder	10	1.7 mm	44	355 μm
2	Moderately coarse powder	22	710 μm	60	250 μm
3	Moderately fine powder	44	355 μm	85	180 μm
4	Fine powder	85	180 μm	—	—
5	Very fine powder	120	125 μm	—	—

pressed with reference to the nominal aperture size of sieve through which powder is able to pass. The relevant grades of powders and sieve number along with nominal aperture size are shown in Table 4-1. The IP 1996 specifies five grades of powder.

Coarse powder : A powder is called coarse powder in which all the particles of which pass through a sieve with nominal mesh aperture of 1.70 mm (No. 10 sieve) and not more than 40.0 % through a sieve with nominal mesh aperture of 355 μm (No. 44 sieve).

In a similar way, other definitions can be written for the contents of the Table 4-1. When fineness of a powder is described by means of a number, it is an indication that all the particles of the powder shall pass through the sieve of which the nominal mesh aperture in μm, is equal to that number.

Normally, for compound powders, fine powders are preferred, while moderately coarse powder is used for the preparation of tinctures. Coarse powder without fines is employed in percolation process. The above mentioned terminology has applications in the production of galanicals. A few examples are given in Table 4-2. The pharmacopœia has prescribed upper and lower limits for the three coarse grades of powder. For two fine grades, the pharmacopœia has prescribed only the upper limit.

TABLE 4-2
Some Examples of Crude Drugs and Nature of Powder Required

Liquid extracts	*Useful parts*	*Grade of powder*
Ashoka	stem bark	coarse
Nux vomica	seeds	moderately coarse
Rauwolfia	roots	moderately coarse
Ergot	sclerotia	moderately fine
Ipecac	root	fine
Ephedra	stem	fine

SIEVES

Sieves are the simplest and sieving is the most frequently used method for size separation.

Construction

Sieves for pharmaceutical testing are constructed from wire cloth with square meshes, woven from wire of brass, bronze, stainless steel or any suitable materials. Sieves should not be coated or plated. There must be no reaction between the material of the sieve and the substance to be sieved.

Types of Sieves

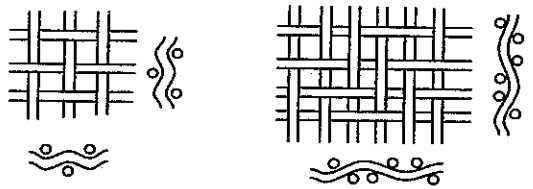
The primary considerations for sieves are given to the size and shape of aperture opening. Square meshes are arranged as per the specifications. Sieves commonly used in pharmaceutical processing include:

- Woven wire sieves
- Bolting cloth sieves
- Bar screens (closely spaced bars)
- Punched plates

Woven wire sieves : Wire woven sieves are general-purpose sieves and widely used in the pharmacy practice. The types of woven wire sieves are:

- Plain weave
- Twilled weave

The nature of sieve surfaces is shown in Figure 4-1. For fine sieving, metal wire woven sieves are used. Common examples are hand sieves. These are included in roller mill, ball mill, etc. during milling. In case of coarse sieves, the wire is generally given a double crimp to preserve the alignment of the wire.



(a) Plain weave sieve (b) Twilled weave sieve

Figure 4-1. The nature of sieve surfaces.

Bolting cloth sieves : Silk, nylon and cotton are generally woven from twisted multi-strand fibres. Nylon cloths are generally designated by their micrometer opening and available in different grades. These are used for the separation of fine powders. Hum-mer screen uses this type of screen.

Bar screens : Bar screens are generally used in handling large and heavy pieces of materials. The bars are fixed in parallel position and held by cross bars and spacers. Bars which taper in thickness from one end to the other are recommended, because they tend to avoid blinding. Grizzlies use these types of screens.

Punched plates (Perforated screens) : These are used for coarse sizing. The screens are prepared by using a metal sheet of varying thickness with perforated holes. The holes may be round, oval, square, or rectangular (Figure 4-2). These types of screens are used in a hammer mill.

A plate with a large number of holes and a small amount of residual metal will have a large capacity, but will wear rapidly and vice versa. In

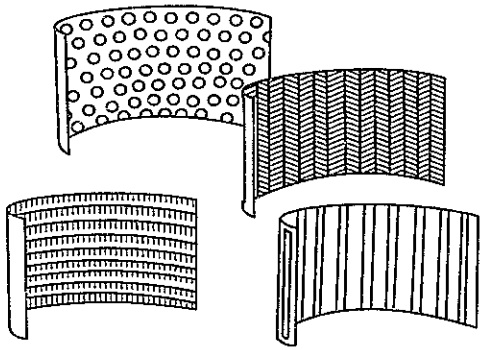


Figure 4-2. The configurations of punched plates or perforated screens.

general, for openings much over 25 mm in diameter, a plate with round perforations is preferred over a wire screen. The applications of screen configurations are given in Table 4-3.

TABLE 4-3
Applications of Various Mill Screen Configurations of Perforated Screens

Perforation shape	*Recommended use*	*Comments*
Round holes	Fibrous materials	Clogs more quickly; lower hole size is limited, because of structural strength.
Herringbone screen (slots)	Amorphous and crystalline materials	Slightly coarse powder than equal-diameter round perforations.
Cross-slots	Amorphous materials and slurries with coarse particles	Same grind size as of equal sized round perforation; finer slot size attainable than round perforations.

Herringbone design : Herringbone design consists of a series of slotted holes repeated across the surface of the screen. These are made at an angle of 45 degrees to the length of the screen. It is preferred for grinding crystalline materials and for continuous operation. If the width of the slot is equal to the diameter of a round hole, it grinds the particles coarser than the round hole. This design should not be used for fibrous materials, as it is possible for fibres to align themselves along the slots and pass through with inadequate size reduction.

Cross-slot screens : In this type, openings are at right angles to the path travelled by milling mechanism. These are used for milling slurries, but not used for fine grinding in hammer mills as it clogs readily.

Standards of Sieves, Dimensions and Notations

Common standards used for sieves are:

(a) Tyler standard sieve series (in USA)
(b) US standard sieve series (in USA)
(c) British standard sieve series (in UK)
(d) German DIN (Deutsche Industrienormein) (in Germany and Europe)
(e) IP standard sieve series (in India)
(f) International test sieve series (ISO) (World wide)

Tyler and US standards can be interchangeable, since the difference between the two standards is less than the allowable tolerance in weaving of the screens. These are also known as *test sieves*. Sieves used for pharmacopœial testing must match with the following specifications:

1. **Number of sieve :** Sieve number indicates the number of meshes per linear length of 25.4 mm.
2. **Nominal size of aperture :** Nominal size of aperture indicates the distance between the two adjacent wires. It represents the size of a square aperture. IP 1996 gives the nominal mesh aperture size for majority of sieves in mm or in μm.
3. **Nominal diameter of the wire :** Wire mesh sieves are made from the wire having the specified diameter in order to give a suitable aperture size and sufficient strength to avoid distortion of the sieve.
4. **Approximate percentage sieving area :** This standard expresses the area of the mesh as a percentage of the total area of the sieve. It depends on the size of the wire used for any particular sieve. Generally, the sieving area is kept within the range of 35 to 40 % in order to give suitable strength to the sieve.
5. **Aperture tolerance average size :** Some variation in the aperture size is unavoidable. This variation is expressed as a percentage and is known as the *aperture tolerance average*. In fact, it is a limit given by pharmacopœia within which a particular dimension or average aperture size can be allowed to vary and still be acceptable for the purpose for which it is used. Fine meshes cannot be woven with the same accuracy as coarse meshes. Hence, the aperture tolerance average is lower for coarse sieves than the fine sieves.

According to IP 2014, a sieve must conform to the specifications given in Table 4-4.

TABLE 4-4
Standards for Sieves—Specifications

Approximate sieve number	*Approximate percentage sieving area*	*Nominal mesh aperture size (mm)*	*Tolerance average aperture size (± mm)*
4	55	4.0	0.136
8	48	2.0	0.07
10	46	1.7	0.06
12	44	1.4	0.05
16	41	1.0	0.03
—	—	µm	µm
22	37	710	25
25	36	600	21
30	38	500	18
36	36	425	15
44	38	355	13
60	37	250	13 (9.9)
85	35	180	11 (7.6)
100	36	150	9.4 (6.6)
120	34	125	8.1 (5.8)
150	36	106	7.4 (5.2)
170	35	90	6.6 (4.6)
200	36	75	6.1 (4.1)
240	34	63	5.3 (3.7)
300	35	53	4.8 (3.4)
350	34	45	4.8 (3.1)

Note : Figures in the brackets refer to close tolerances and those without brackets refer to full tolerances.

Comparison of Ideal and Actual Screens

An *ideal screen* would sharply separates the feed mixture in such a way that the smallest particle in the oversize would be just larger than the largest particle in the undersize.

Such an ideal separation defines a cut diameter, D_{pc} that makes the point of separation between the fractions. Usually, D_{pc} is chosen to be equal to the mesh opening of the screen.

An *actual screen* is the one, which does not give perfect separation about the cut diameter.

In an actual screen, the overlap between the smallest particle in oversize and the largest particle in undersize is more pronounced, when particles:

- are needle like, fibrous.
- tend to aggregate.
- tend to strike the screen surface endwise and pass through.
- tend to strike the screen sidewise and retained.

Commercial screens usually give poor separations than testing screens of the same mesh opening when operated on the same equipment.

Comment 4-1. Why are sieves designated by sieve number rather than (mesh) aperture size?

Comment 4-2. What is the difference between nominal size of aperture and nominal diameter of the wire?

MODES OF MOTION IN SIZE SEPARATION

Screening is a method of separating particles according to size alone. The basic technique involved is passing the particles through a series of sieves of uniform size. In this, the particles drop through the openings due to gravity. Coarse particles can drop easily through large openings, but it is difficult to screen the fine powders. This process can be hastened by inducing some type (mode) of motion (movement) to the particles. Size separation is basically assisted by three methods.

1. Agitation
2. Brushing
3. Centrifugal force

These modes of shaking help to shake the material so that sieving will be quick and entire sieving area can be utilised.

Agitation Separation

Sieves are agitated in a number of ways. Some of them are discussed below.

Oscillation : The sieve is mounted in a frame that oscillates back and forth, i.e. reciprocal motion (Figure 4-3). It is a simple method, but the material may roll on the surface of the sieve. The motion is parallel to the plane of the sieve. The sieves can be slightly inclined. The reciprocating motion is induced by means of an ordinary eccentric on a rotating shaft.

Vibration : The sieve is vibrated at high speed by means of an eccentric device (Figure 4-4) either electrically or mechanically. Rapid vibration is imparted to the particles that helps the powder to pass through the sieve. Electrically vibrated screens are particularly useful in the chemical industry, e.g. hum-mer screen. They handle light, fine and dry materials successfully. Inducing vibrations also prevents blinding of meshes.

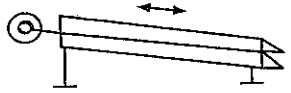


Figure 4-3.
Oscillatory motion of screen.

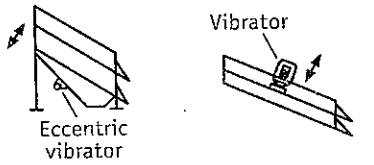


Figure 4-4.
Vibrating motion of screens.

Gyration : In this method, a system is made so that sieve is on rubber mounting and connected to an eccentric flywheel (Figure 4-5). This gives a rotary movement of small amplitude to the sieve, which in turn gives spinning motion to the particles that helps to pass them through the sieve.

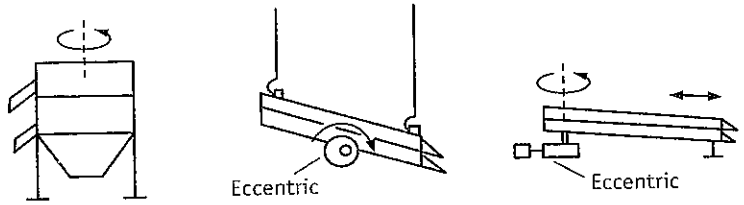


Figure 4-5. Gyratory motions of screens or sieves.

Gyratory screens are box like equipment, either round or square, with a series of screen cloths arranged one above another (Figure 4-5). Most gyratory screens have auxiliary vibrations caused by balls bouncing against the lower surface of the screen.

Agitation methods are not continuous methods. However, these can be made continuous by inclination of the sieves. Separate outlets are made for undersize and oversize particles. Normally, all the three modes of agitation are used simultaneously for an efficient size separation. Rotex screen works on this principle.

Advantages : (1) Agitation methods are inexpensive.
(2) Simple and rapid.

Disadvantages:

(1) Agitation methods have lower limit of the particle size.
(2) If the powder is not dried, apertures become clogged with particles leading to improper sieving.
(3) During agitation, attrition (particles colliding with each other) occurs causing size reduction.

Brushing Separation Method

In this case, a brush is used to move the particles on the surface of the sieve and to keep the meshes clear. The brush is rotated in the middle in the case of a circular sieve, but spiral brush is rotated on the longitudinal axis in case of horizontal cylindrical sieve. One example is brush sifter (Figure 4-6). This is used for size separation of greasy or sticky powders such as waxes and soaps.

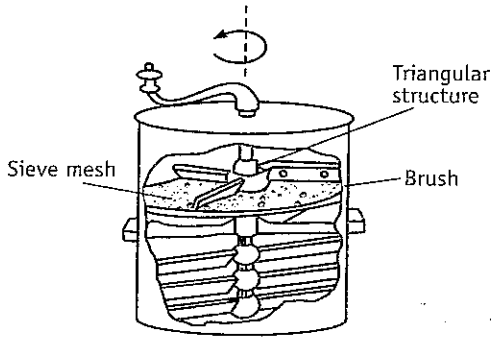


Figure 4-6. Brush sifter.

Centrifugal Separation Method

In this method, a high-speed rotor is fixed inside a vertical cylindrical sieve, so that on rotation the particles are thrown outwards by centrifugal force. The currents of air can be generated by means of a jet of air into the equipment, which helps in separating the particles. A few examples of equipment that work on this principle are cyclone separator and air separator.

Advantages:

(1) Centrifugal methods are extremely useful in cases where conventional sieving tends to block the sieves.
(2) Extremely useful for fine powder, because sieves have the limitation of mesh size.

Comment 4-3. What is meant by blinding in size separation? How is it prevented?

TESTING OF POWDER— SIEVE ANALYSIS

The milled material is subjected to size separation in order to obtain the powder of desired size or size distribution. Size distribution analysis is important in different areas as mentioned below.

- Quality control tool for the analysis of raw materials.
- Testing the efficiency of a size reduction equipment or process.
- Optimising the process conditions such as method of agitation and time of screening.

- Selecting the sieve system for commercial equipment.

Errors can arise if the sieves are overloaded or if insufficient time is allowed for the particles to pass through.

Sieve Shaker Machine

Principle : The powdered drug is separated according to its particle size using a set of sieves in a nest. These are subjected to different types of agitation, so that size separation is rapid.

Construction : Standard sieves of different mesh numbers are available commercially as per the specifications of IP and USP. These sieves are fixed in a mechanical shaker apparatus (Figure 4-7).

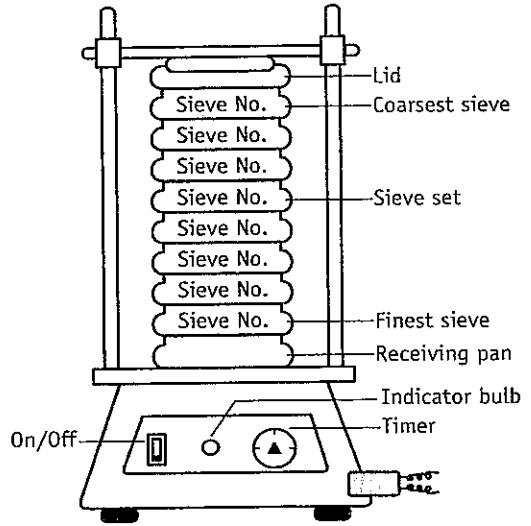


Figure 4-7. Laboratory sieve shaker machine.

Working : Sieves are arranged in a nest with the coarsest at the top. A powder sample (50 g) is placed on the coarsest sieve (Figure 4-7). This sieve set is fixed to the mechanical shaker apparatus and shaken for a certain period of time (20 min). The powder retained on each sieve is weighed.

Practical considerations : Care should be taken in order to get reproducible results. The type of motion influences sieving; vibratory motion is most efficient, followed by side-tap motion, bottom-pat motion, rotary motion with tap and finally rotary motion. The type of motion and intensity of the shaker are fixed and standardized. Shakers are commercially available.

Other factors are weight of the sample and duration of shaking. Sieves produced by photo-etching and electro-forming techniques are used to get

a better estimate of the size distribution analysis with a lower limit of estimation of particle diameter 50 μm.

Advantages : It is inexpensive, simple and rapid with reproducible results.

Disadvantages : (1) Lower limit of particle size is 50 μm.

(2) If powder is not dry, apertures get clogged with particles, leading to improper sieving.

(3) During shaking, attrition (particles colliding with each other) occurs causing size reduction of particles. This leads to error in estimation.

Variants : *Electromagnetic sieve shaker*—It is useful for analysing powders under controlled conditions. *Sonic sifter*—This apparatus utilises sonic oscillations. A mechanical pulse action is used to reduce blinding and agglomeration in the sub-sieve sizes.

Alpine Airjet Sieve

Principle : In the Alpine airjet sieve, sieving action involves the application of a jet of air on one side of the sieve and suction on the other side. The material is maintained in a fluidised state on the screen by a stream of air. Vacuum is applied below the screen, so that the undersized powder is sucked through the sieve.

Construction : The construction of a Alpine airjet sieve is shown in Figure 4-8. It consists of a metal housing into which the sieve mesh is fitted. Sieve cover is placed in such a way that an air-tight seal is obtained. A slit is provided such that its upper edge is in level with the upper edge

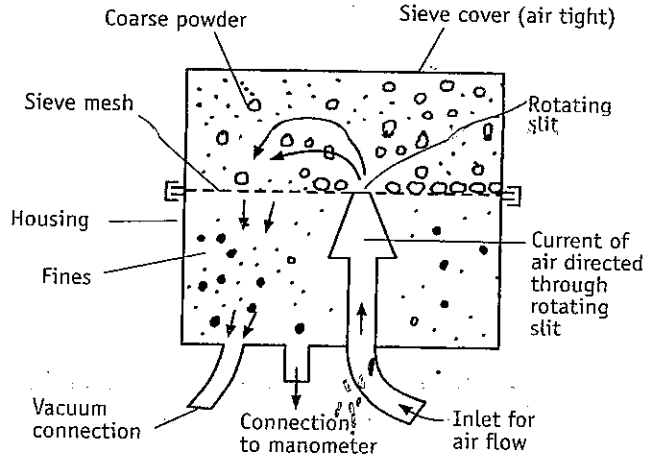


Figure 4-8. Alpine airjet sieve.

of the housing. Provision is made to pass airjet below the slit. Suction line is provided below the sieve, which can be controlled with the help of a manometer.

Working : A small amount of powder (about 10 g) is spread on the sieve. The cover is placed in position. The slit is set into rotation by sending a jet of air from below. The powder is fluidised in the upward jet of air. The suction is adjusted until the manometer reads about 27 kPa. The vacuum (in the interior of housing) sucks the undersized powder through the sieve. The material is recovered.

Sieving is continued for two minutes and the residual powder is weighed. This powder is transferred to the next sized mesh with a fine brush. This process is continued until all fractions are collected from the sample, by changing the sieve meshes as well as magnitude of the suction.

Uses : Alpine airjet sieve method is used for the analysis of powder for its size distribution. This method is particularly useful in cases where conventional sieving tends to block the sieves below about 80 μm.

Advantages : (1) In Alpine airjet sieve, fluidisation of powder prevents blocking of the mesh.

(2) It is a rapid method once the mesh is placed and gives reproducible results.

(3) It is very useful for fine powders.

Disadvantages : (1) The capacity of Alpine airjet sieve is limited. Therefore, it is not useful for large-scale separations.

(2) This method is tedious, because each time only one particle size powder is obtained.

Data Presentation

Frequently a powder is assigned by a mesh number of the screen through which it passes or on which it retains. It is expressed in terms of arithmetic or geometric mean of the two sieves, i.e. a powder passing through a 36 mesh and retained on 44 mesh sieve is assigned an arithmetic mean diameter of (425 + 355)/2 or 390 μm. This is reported as undersize.

Data Analysis

The weight of sample retained on each sieve is considered for the analysis. The data are analysed for normal, log-normal, cumulative percent frequency distribution and probability curves. Along with these, different mathematical expressions are also used such as average particle diameter, geometric mean weight diameter, etc. For further analysis refer the book, "*Textbook of Physical Pharmaceutics-II*" by C.V.S. Subrahmanyam, Vallabh Prakashan, Delhi.

Comment 4-4. The sensitivity of the sieve shaker is 50 μm. Explain.

Comment 4-5. Alpine airjet sieve equipment is used for standardization, while industrial equipment is used for the separation of sizes. Justify.

EQUIPMENT FOR SIZE SEPARATION

A wide variety of equipment have been developed differing in the scale of operation, ruggedness, method of movement of material and material of construction. Some factors to be considered are:

(a) wear of the sieves
(b) blinding
(c) machine noise

General Classification of Screening Equipment

The screening or sieving machines may be divided into different classes.

(1) *Grizzles* : For coarse materials above 50 mm — large lumps.
(2) *Revolving screens* : Separation above 13 mm — trommels.
(3) *Shaking screens* : Separation from 13 mm downwards to fines.
(4) *Vibrating screens* : Coarse size (13 mm) to fines.
(5) *Oscillating screens* : For fine particles
(6) *Fluidised systems* : For very fine powders.

A few equipment are described below.

Critical Quality Attributes—Size Separation

The critical quality attributes (CQAs) along with process parameters (PPs) are recorded (Figure 4-9). The size reduction is considered in the context of production of tablets, after wet milling or dry milling. The upstream operation must be drying of granules and the downstream is size separation or blending. Milling and size separation are more commonly conducted simultaneously. For a given set of conditions, the attributes related to content uniformity are critical: average size, size distribution, flow properties and densities.

The process parameters optimized as: feed rate, screen size and time of screening. These are controlled during the size separation and are prefixed as standards with limits for a given set of conditions. Production control charts are used for monitoring the standards. The above are the general characteristics, but a few may change depending on the screen type.

Shaking Screen

Principle : Particles of different sizes are separated by passing them through a sieve, which oscillates to and fro continuously.

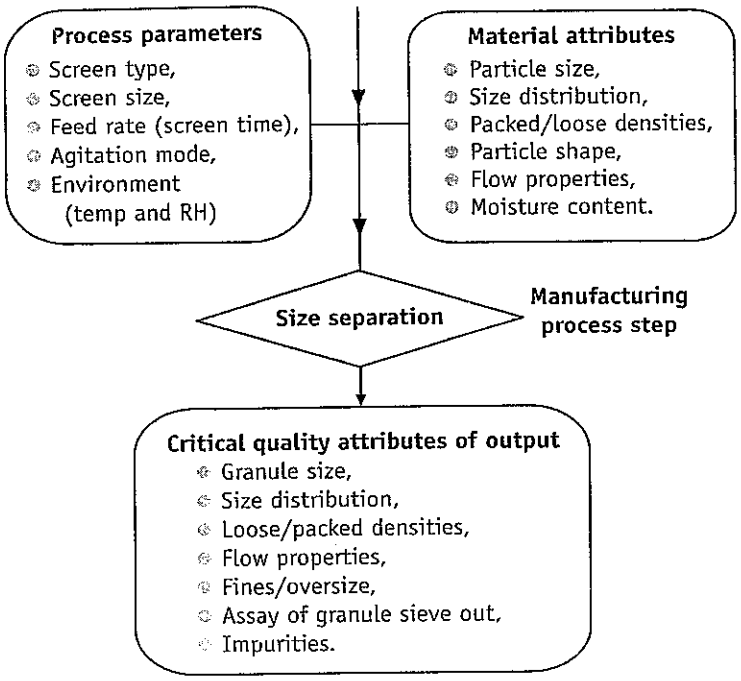


Figure 4-9. Process parameters and CQAs for size separation as an independent operation in the production of tablets – Dry granules size separation.

Construction : The construction of a shaking screen is shown in Figure 4-10. Shaking screen consists of metal frame to which a screen is fixed at the bottom. The screen cloth may be riveted directly or fitted using a removable bolted frame. The metal frame can be arranged horizontally or in inclined position. It is suspended by means of hanger rods, so that it can move freely. The side of the metal frame is connected to an ordinary

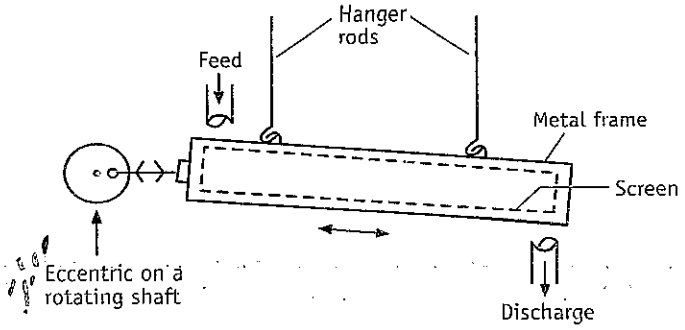


Figure 4-10. Shaking screen in inclined position.

eccentric on a rotating shaft. The entire frame can experience reciprocating motion.

Working : The screen is allowed to shake in a reciprocating motion. The feed (material to be screened) is introduced on to the screen from a side. Therefore, fine particles get screened off initially. The remaining material moves forward during the motion of the frame and gets separated. Thus, the desired size particles can be obtained from the material.

The **advantage** of shaking screen requires low head-room and low power requirement.

The **disadvantage** are, shaking screen requires high cost of maintenance of screens and supporting structures. Its capacity is low.

Variants : The shaking screen system may be vibrated to keep the particles moving and preventing blinding. It is used when large capacity and high efficiency is desired.

Rotex Screen

Principle : Rotex screen works on oscillating agitation (back and forth) by means of an eccentric mechanism. Further, vibrations are caused by balls bouncing against the lower surface of the screen cloth. This rapid motion helps the particles to roll on the surface of the screen and separate out.

Construction : The construction of a Rotex screen is shown in Figure 4-11. The screen is slightly inclined at 5 degrees. A coarser supporting screen is placed below a coarse screen (Figure 4-11a). Between the screens, wooden blocks are placed at different intervals. Between the wooden blocks, a number of rubber balls are placed. This two-sieve system represents one unit. Several such units are arranged in the desending order, i.e. sieve of larger opening at the top and smaller one at the bottom (Figure 4-11b).

If more number of sieve sizes are desired, n screens are arranged in a similar manner to obtain $(n + 1)$ fractions. This assembly is supported on sliding contacts at the lower end. The upper end of screen system is connected to an eccentric pin on a flywheel.

Working : The screen system is allowed to agitate with the help of eccentric. The shaking motion of the screen causes balls to fly between the screens. As they strike the inclined sides of the wooden blocks, the balls deflect upward and strike the underside of the screening cloth and thus prevent the blocking of the mesh (Figure 4-11a). The feed is introduced at the elevated end of the screen. The material passes through the upper screen and reaches the next screen. This process continues until all the material is separated into fractions. The fractions are collected separately at the outlet point.

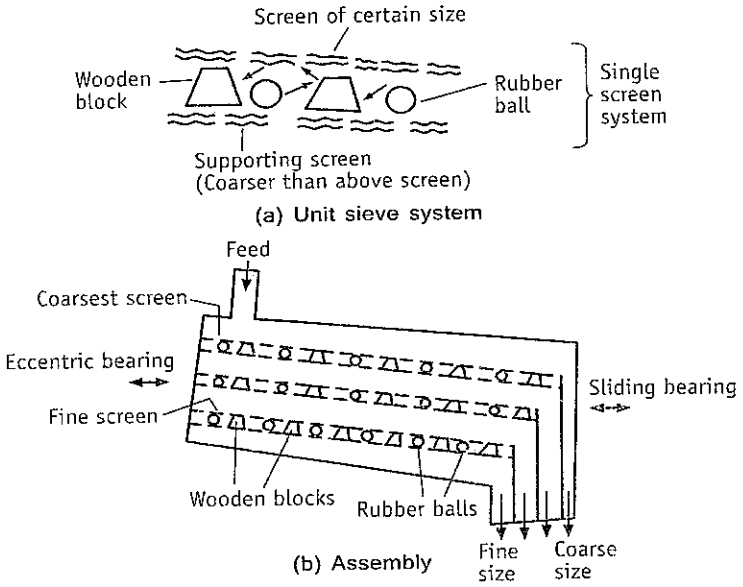


Figure 4-11. Rotex screen.

Uses : Rotex screen is used for handling a variety of chemicals usually dry materials. Granular matrices and powdered foods are also size separated by Rotex screen. Therefore, these are used extensively as standard equipment in many chemical and processing plants for handling fine separations.

Cyclone Separator

Principle : In cyclone separator, centrifugal force is used to separate the solids from fluids. The separation process depends not only on the particle size, but also on the density of particles. Depending on the fluid velocity, the cyclone separator can be used to separate all types of particles. It is also possible to allow fine particles to be carried by the fluid.

Construction : The cons-truction of a cyclone separator is shown in Figure 4-12. It consists of a short vertical, cylindrical vessel with a conical base. The upper part of the vessel is fitted with a tangential inlet. The outlet (solid outlet) is arranged at the base. Fluid outlet is provided at the centre of the top portion, which extends inwardly into the separator.

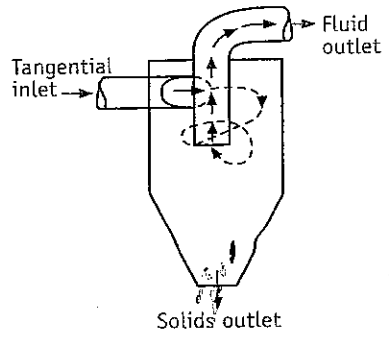


Figure 4-12. Cyclone separator.

Such an arrangement prevents the air short-circuiting directly from the inlet to the outlet of the fluid.

Working : The solids to be separated are suspended in a stream of gas (usually air). Such a feed is introduced tangentially at a very high velocity, so that rotary movement takes place within the vessel. The centrifugal force and vortexing throws the solids to the walls. As the speed of air diminishes, the particles fall to the conical base and are discharged through the solid outlet. The fluid (air) can escape from the central outlet at the top.

Uses : (1) Cyclone separator is used to separate the solids from gases.

(2) It is also used for size separation of solids in liquids.

(3) It is used for separating the heavy or coarse fraction from fine dust.

Variants : Cyclone separators are also used for size separation of solids suspended in a liquid such as water. Such separators are known as *wet* or *liquid cyclone*. One such apparatus used for this purpose is *Dorrclone*.

Air Separator

Principle : In air separator, centrifugal force is used to separate solids. The air environment is obtained by means of rotating disc and blades. To improve the separation, stationary blades are used. By controlling these blades and the speed of the rotation, it is possible to vary the size at which separation occurs.

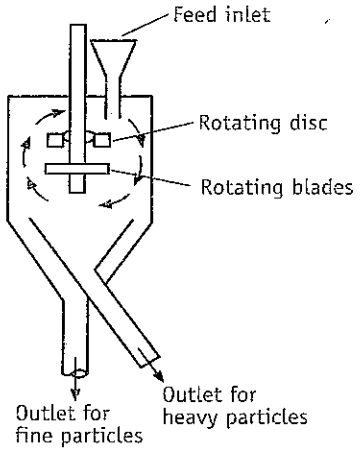


Figure 4-13. Air separator.

Construction : The construction of an air separator is shown in Figure 4-13. It consists of a cylindrical vessel with a conical base. The feed inlet is fitted to the upper part of the vessel. The rotating disc and rotating blades are attached to the central shaft to produce air environment. At the base of the vessel, two outlets are provided; one for fine particles and the other for heavy particles.

Working : The disc and blades are allowed to rotate by means of a motor. These produce a current of air as shown by the arrows. The sample powder is introduced through the feed inlet. The feed falls on the rotating disc. The fine particles are picked up and carried into space, where air velocity is sufficiently reduced. The fine particles are dropped and are

ultimately collected at the outlet meant for the fine particles. The heavy particles, which fall downward, are removed at the outlet meant for heavy particles.

Uses : Air separators are often attached to the ball mill or hammer mill to separate and return over sized particles for further size reduction.

Bag Filter

Principle : In a bag filter, size separation of fines (or dust) from the milled powder is achieved in two steps. In the first step, the milled powder is passed through a bag filter (cloth) by applying the suction on the opposite side of the feed entry. This facilitates the separation. In the next step, pressure is applied in order to shake the bags so that powder adhering to the bag falls off, which is collected from the conical base.

Construction : The construction of a bag filter is shown in Figure 4-14. It consists of a number of bags made of cotton or wool fabric. These are suspended in a sheet metal container.

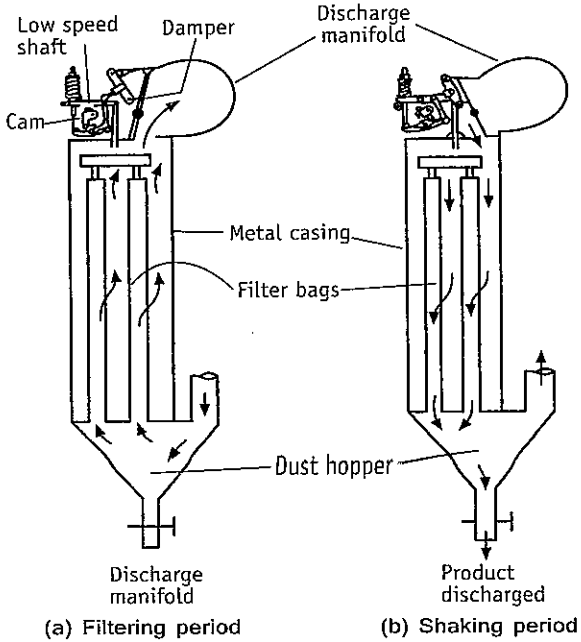


Figure 4-14. Bag filter.

A hopper is arranged at the bottom of the filter to receive the feed. At the top of the metal container, a provision is made for the exhaust. Adjacent to this, a bell crank lever arrangement is made to bring the filters to normal atmospheric conditions.

Working : The working of the bag filter consists of two steps. In the first step, the feed is separated from air by passing it through the cloth bags. In the subsequent step, the bags are shaken to collect the fines that are adhered to the bags. These two steps follow in succession and are controlled at different intervals with the help of a bell crank lever arrangement.

Bell crank lever arrangement : In this mechanism, a shaft with a cam is allowed to rotate at a low speed. During rotation, the cam can either press the bell crank lever or does not come into contact. Depending on this mechanism, the damper changes its position. The damper is a useful mechanism, which allows the two steps to occur as shown below.

Step	*Mechanism*	*Movement of damper*	
		Contact between bags and suction	*Contact between bags and atmosphere*
Filtering period	Cam does not press the bell crank lever (Figure 4-14a)	opens	closes
Shaking period	Cam presses the bell crank lever (Figure 4-14b)	closes	opens

These changes occur at intervals of a few minutes.

Filtering period : The exhaust fan positioned at the top keeps the bags under less pressure than atmospheric pressure. The gas containing fine particles (or dust) enters the hopper, as shown with arrows in Figure 4-14a, and passes up. The gas feed passes through the fabric of bag. During this process, the fines (or dust) are retained in the bags, while the gas reaches the top of the casing. Because of air, the bag remains taut during filtering operation.

Shaking period : Since vacuum is cut off in the chamber, air from outside enters the casing and passes through the bags. This results in violent shaking of the bags, so that the dust and fine particles are displaced from the bags and fall into the conical base. These are then removed at intervals.

Such devices are entirely automatic in their action and can be designed to affect very large filtering surface per unit floor space.

Uses : Bag filters are used along with other size separation equipment, e.g. a cyclone separator. Bag filters are used to remove the fines from cyclone discharge. Bag filter is connected to the discharge end of the fluidized energy mill.

Advantages : (1) Bag filter is extremely useful for removing fines, which cannot be separated by other methods.

(2) These can be used even to remove dust. The ordinary household vacuum cleaner is a simple bag filter.

Disadvantage : Bag filter is not size separation equipment as such.

Scrubbers

Principle : Scrubbers are used to remove solid particles or liquid droplets from gases. These utilise water to scrub the particles (droplets) by countercurrent contact. The principles of inertial impact and absorption are responsible for separation.

Construction : The construction of a water scrubber is shown in Figure 4-15. It consists of a cylindrical shell with a conical bottom. It has the provision to allow the gas to enter tangentially. Provisions are made to introduce water at the top and water outlet at the bottom. A series of deflectors is mounted on the top of the stationary vanes, which are in turn supported by annular shelves. Air outlet is provided at the top.

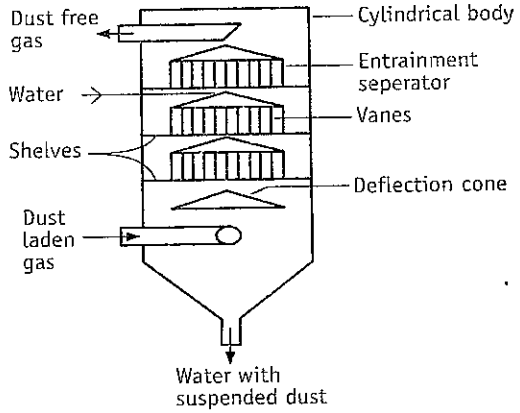


Figure 4-15. Scrubber-dust washer.

Working : The gas carrying the suspended particles enters tangentially at the bottom and passes upwards. At the same time, curtains of water fall from the deflector cones. The gas passes through the sheets of liquid (towards the center of the tower). The gas changes the direction and passes through the vanes. Thus, several contacts permit the higher entrainment of droplets. The water moves out from the top of separator. This equipment combines the action of cyclone (entrainment separator) for separation of entrained droplets of water. Finally the gas leaves the dust washer.

Variants : Venturi scrubber is a variant in which a venturi tube is placed in the line. The gas flows through the tube at high velocity. From the upstream of venturi throat, the scrubbing liquid is introduced at low pressure.

The gas collides with the liquid, so that the sheet of liquid is disrupted and liquid particles are rapidly formed. The velocity of gas decreases at the diverging section, and small particles (in the gas) are wetted by the finely divided liquid droplets. Then, particles coalesce. The discharge of scrubber goes to a cyclone separator where coalesced particles are removed from the gas stream.

Comment 4-6. What is the use of two screen-set in Rotex screen?
Comment 4-7. In what way is air separator different from sieve shaker?

SETTLING BEHAVIOUR OF SOLIDS — METHODS

Settling is a process of sedimenting the particles of different sizes.

Settling is achieved by gravity or centrifugal force. Gravity sedimentation is described using water (or liquid) as a medium. Dry sieving may lead to difficulties with some materials. Wet sieving is efficient than an equivalent dry process.

Size Separation by Settling

Principle : When powder is admitted horizontally into a small water tank, particles start to settle. A similar situation is observed, when the powder is placed in a flowing stream of water (Figure 4-16). Two particles have different settling rates. These are placed in a upward flowing stream of water and the velocity of water is adjusted to lie between the settling rates of the particles. In the first stage, the particles gain acceleration from zero to terminal velocity. In the second stage, the particle maintains the terminal velocity. The slower settling particle is carried along with the liquid, while the faster settling particle moves downward against the water stream. After travelling a certain distance, the slower settling particle also moves downwards. Thus, separation of particles is achieved. The fluid is recovered and sometimes reused.

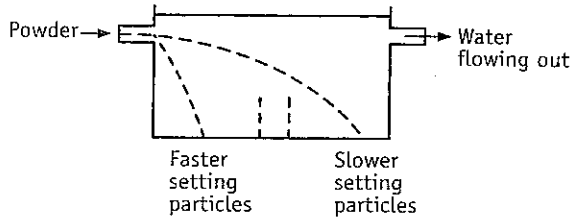


Figure 4-16. Simple hydraulic separation — Continuous sedimentation tank.

The settling rate of particles depends on particle size, particle shape and particle density. Settling methods do not give separation of particles of one size, but gives a mixture of sizes with an average diameter of one fraction. At another place, a different fraction of particles is obtained.

The principle of settling of particles is used for size separation in the following conditions.

- When the particles are too small to use a screen effectively.
- When large particles (high amount) of material is to be handled.

Applications : Powder is deliberately suspended in fluid to obtain separation of the particles. Dust particles are removed from water stream and gases to eliminate contamination. Solids are removed from liquid waste by this method.

Disadvantages : It is a batch process. Discrete particle fractions cannot be collected, as sample may contain particles of different diameters.

Free Settling

Free settling implies that particles settle independently, without any interference of other particles in the fluid.

Free settling is achieved, when the concentration of particles is low and the volume of fluid is high. The effect of the walls is negligible. The particles settle under the influence of gravity. As the particle moves down, the fluid offers a greater frictional resistance. When the resisting force is exactly equal to the force of gravity, a condition is reached at which the acceleration of particle becomes zero. From this time onwards, the settling of particle follows a constant velocity. These conditions are similar to the laminar flow. This velocity is called *terminal settling velocity*. This velocity can be obtained from Stokes equation. For describing the flow pattern of the fluids, Reynolds number is also utilised. The Stokes equation is given below.

$$U = \frac{D^2 (\rho_s - \rho) g}{18 \eta} \quad \ldots(1)$$

where U = Terminal settling velocity, m^3/s
D = Diameter of the particles, m^3
ρ_s = Density of the particle, kg/m^3
ρ = Density of fluid, kg/m^3
g = Acceleration due to gravity, m/s^2
η = Viscosity of the medium, Pa.s

As per equation (1), terminal settling velocity for different flow patterns can be described as follows.

- *Laminar region*—terminal velocity is equal to square of the particle diameter.
- *Turbulent region*—terminal velocity is almost proportional to the particle diameter.

Whatever is the condition, the settling velocity is so slow and the size of particle is so small that it is impracticable to produce size separation. However, sedimentation usually involves settling velocities below the critical value. Hydraulic classification process may involve particles of one material, but of different sizes, two or more materials of different specific gravities, but of same size.

Hindered Settling

Hindered settling implies that light particles are pushed by heavier particles, on account of particle-particle collisions.

When the concentration of solids is high, particles are close to each other and collide continuously. Stokes law is not applicable in this case. The settling velocities are lower in the hindered settling due to variety of reasons.

- There is an appreciable displacement of fluid opposite to the direction of motion of solid particle, due to high concentration of solids.
- The available effective cross section of liquid is restricted.

For hindered settling, settling velocities are predicted for the concentration of uniform spheres. When the size distribution of particles is wide, particles are irregular in shape or when flocculation of fine particles is observed, it is more difficult to predict settling velocities.

Settling — Clarifiers and Thickeners

In a suspension, if the solids remain as an individual particle of a few micrometers (< 5.0 μm in diameter), the gravity settling rate will be very low due to Brownian motion. In fine suspensions, the particles may form agglomerates and these settle at reasonable rates. Agglomeration can be promoted by adding flocculating agents, namely ions, polymers (ionic and nonionic), alumina, sodium silicate, etc. Further, flocculated suspensions are used as dosage forms. These preparations are known as *thickeners*. The settling behaviour of the floc solids is different from that of denser solids.

Flocs : The material to be settled is in the form of flocs (aggregates). Further, aggregates have high porosities and retain considerable amount of water within them. The flocs are assumed to be uniform in size and shape, so that they settle at uniform velocities under conditions of hindered settling in the initial stages. The flocs upon settling, get compressed to a certain extent by subsequent settling of flocs. The sedimentation of flocs is hindered by the other solids to a certain extent.

The sedimentation behaviour can be studied using glass cylinder (Figure 4-17). Several stages in the settling of flocculated suspensions are described below, using the stage 'b' tube.

- Initially the dispersion is uniform (Tube 'a' of Figure 14-17).
- After sometime, a layer of clear water is observed at the top (A portion of tube b).
- Coarse particles settle at first to the bottom. It is represented by zone D.
- The next settled solids form a transition zone, i.e., zone C.
- The boundary between the layers C and D is usually obscure (not visible) and is marked by vertical channels through which water is escaping from the lower layer which is under compression.
- There upon a zone of partly thickened material above.
- Then a zone of B of the material at original concentration.

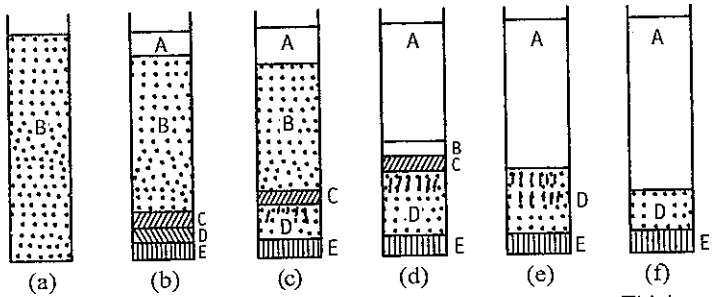


Figure 4-17. Typical slurry settling tests-Batch process — Thickeners.

As settling continues, the clear zone increases and the zone B decreases (Tube d). Subsequently zone B disappears (Tube e). The zone C gets compressed on the accumulation of solids above. This results in disappearance of transition zone (Tube e). This further compresses the zone D. Compression breaks the floc structures, the void liquid gets expelled to the zone above. After a particular stage, sedimentation stops.

Slurries vary in their settling rates and the relative heights of different zones, during settling. The experimental studies of settling rate for different initial heights and concentrations are needed for the design of the thickner.

Classification Methods

Classification methods of a powder are the particle separation methods based on the principle of settling rate of particles into different fractions of narrow particle size range.

Classification method is not a size separation method as obtained using sieves. Even the mixture contains materials of different densities, and sizes, classification is possible into coarser fraction containing heavier components and finer fraction richer in lighter component. If separation takes

place based on differential densities, devices are known as sorting classification. The principle involved is sink-and-float or differential settling. *Differential settling* methods utilise the differences in terminal velocities that can exist between substances of different densities.

The construction of hydraulic classifier is shown in Figure 4-18. In this type, the sorting columns have same diameter, but water streams are entered at different velocities from the bottom of each column. The size of the particles of each vessel is increased, partly because the amount of liquid to be handled increases and partly to reduce in stages the surface velocity of fluid flowing from one vessel to another vessel.

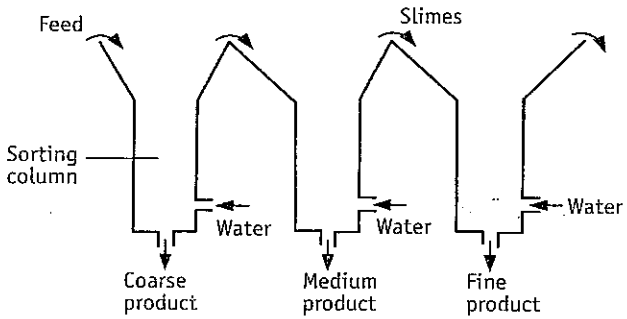


Figure 4-18. Hydraulic classifier.

Applications : Hydraulic classifiers (fluid classifier) are useful in the lower size ranges. Sedimentation tests are applied to light kaolin in order to limit the coarseness of the powder. Light kaolin must consist of fine particles. Further, therapeutic activity depends on the adsorption properties, which are related to surface area. Similarly, chalk is often subjected to wet-grinding followed by sedimentation or elutriation with water.

Disadvantages : Classification methods do not give accurately sized products as screens do. These methods are used to convert dilute slurry of fine particles into a clarified liquid or a concentrated suspension. These are simple methods and applicable only for batch processes. Discreet particle fractions cannot be collected.

Double Cone Classifier

Principle : The particles in the powder are separated by regulating the hydraulic water supply and the height of inner cone by hand wheel.

Construction : The construction of a double cone classifier is shown in Figure 4-19. It consists of two cones of different sizes placed one inside the other. Both cones are pointed downwards. Provision is made at the bottom for the entry of water. In the upper top portion, feed inlet is arranged. A mixing port is introduced at the centre of the inside cone.

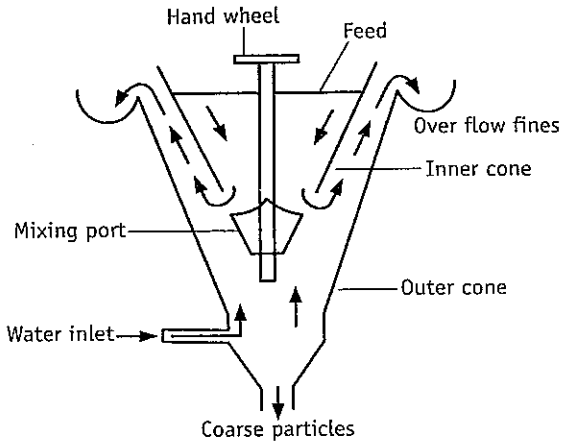


Figure 4-19. Double cone classifier.

Working : The feed of powder is introduced into the inner cone. Water is introduced through the cone and moves upward direction. The mixing port is allowed to rotate. The feed is forced towards the periphery of outer cone (centrifugal effect). Such a mechanism allows the effective interaction of particles and water. The particles under settling impact the uprising water stream. The fine particles are carried upward and escape through the peripheral lounder. The coarse particles settle into the chamber and drawn off at different intervals.

Uses : Wet and dry sizing can be done using the double cone classifier. Corrosive and abrasive materials can also be handled.

Advantages : The cost of installation is cheap. Operation of the equipment is easy.

Disadvantage : The solubility of solid in the fluids must be low.

Comment 4-8. What are the differences between sieving and classification methods in case of size separation?

ELUTRIATION METHODS

Elutriation is a method of separation of particles in a powder based on the low density of fine particles and high density of the coarse particles using fluid flow.

Elutriation and sedimentation are different in one respect (Fig. 4-20). In case of sedimentation, particles move in the direction of gravitational force, while in elutriation, some particles move against the gravitational force. The arrows are vectors, showing direction and magnitude of particle movement. In sedimentation, fluid is stationary and particles settle based

on the particle velocity. In elutriation, fluid flows in opposite direction of the settling movement. The upward velocity of fluid is less than the settling velocity of the particles. Hence, time is an important factor. In practice, particles can be seen to rise with the fluid and then to move outwards to the tube-wall, where the velocity is lower and these start to fall.

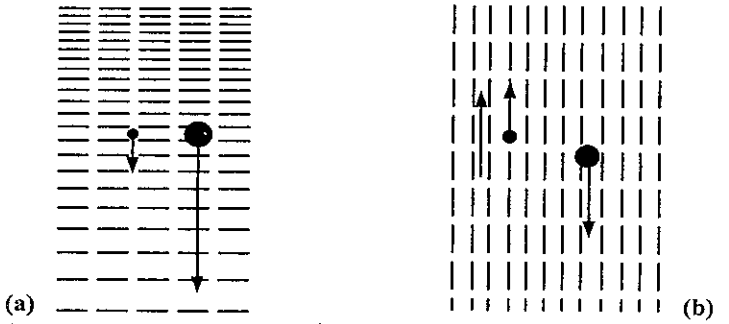


Figure 4-20. Comparison of (a) sedimentation and (b) elutriation.

Uses : Elutriation technique is applicable to insoluble solids such as kaolin or chalk, which are subjected to wet grinding followed by sedimentation or elutriation.

Advantages : Elutriation process is a continuous process. Separation of size fraction is quick as compared to other methods. The apparatus is more compact than that are used in sedimentation methods. Depending on the number of fractions required, the same number of tubes of different area of cross-section can be connected.

Disadvantages : The suspension (or solids) should be diluted, which may not be desirable in certain cases.

Static Tank Method

The construction of elutriating tank is shown in Figure 4-21. The dry powder or paste made by levigation is kept in an elutriating tank. It is

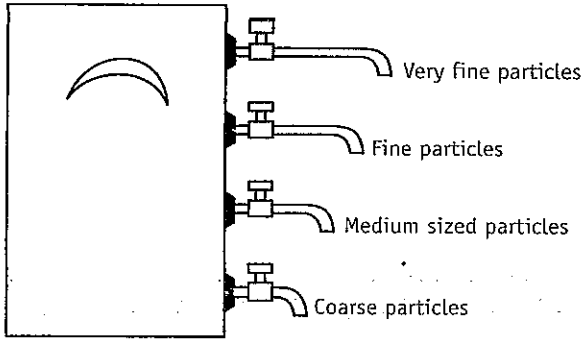


Figure 4-21. Elutriating tank — Static method.

mixed with a large quantity of water. The solid particles are distributed uniformly in the liquid during stirring. Then the particles are allowed to settle. Depending on the density, the solid particles may either settle down or remain suspended in water. Samples are withdrawn at different heights through the outlets. The powders are dried and thus various size fractions are collected.

Single Separation With Mobile Liquid

In this elutriating process, the particles are suspended in a moving fluid, generally water. The apparatus consists of a vertical column of glass tube (or cylinder) with an inlet near the bottom for introducing the suspension (Figure 4-22). An outlet is provided at the top for the overflow of fluid of fine particles.

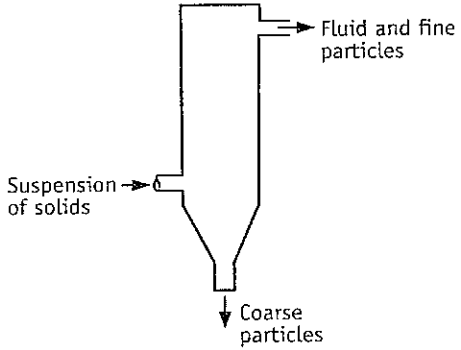


Figure 4-22. Elutriation — Simple separation.

The feed is introduced from the bottom. The movement of particles is as follows. Generally, fluid is allowed to flow upward direction, while particles move downwards due to gravitational force, depending on the experimental conditions.

- If the upward velocity of the fluid is less than the settling velocity of the particles, sedimentation occurs.
- Conversely, if the settling velocity of the particle is less than the upward fluid velocity, particle moves upwards with the fluid flow.

Thus, the fluid flow (velocity) contributes significantly for the separation of particles. Therefore, in elutriation, powder is divided into different size fractions. A single column will give single separation into two fractions.

Separation as Multiple Fractions

Several vertical liquid columns may be arranged in series (Figure 4-23). Each subsequent tube must have an increasing area of cross section. In such a case, each column will give the separation of only two fractions.

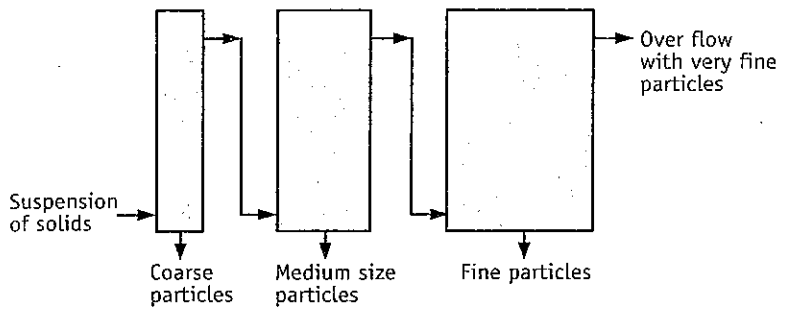


Figure 4-23. Elutriation — Multiple fraction separation

The velocity of the fluid decreases in successive tubes, as the area of cross section increases. Thus, several fractions are separated, collected and dried.

Comment 4-9. What are the differences between sedimentation and elutriation methods in the size separation?

Comment 4-10. Water soluble substances can be separated into different sizes by elutriation method. True or false. Justify.

SELECTION OF SIZE SEPARATION EQUIPMENT

Selection of specific size separation is the pharmacopoeial requirement. The most efficient method should be selected based on the particle properties.

- If particles are already present in suspension as obtained from colloidal mill (water) or fluid energy mill (air), then separation can be achieved by elutriation and cyclone separation. In these cases, separation is the most important, because oversize material is returned to the mill.
- As many pharmaceutical solids are water soluble, separation must be restricted to the use of air (cyclone separator or air separator) or sieve methods.

The final choice of the equipment depends on the feed material, nature of finished product, facilities available and costs in terms of procurement and maintenance.

Summary

Size separation is an operation involving the separation of a mixture of particles into two or more portions by means of screening surfaces. The other nomenclatures are sieving, sifting, classifying and screening. Powders are either collected from natural sources or processed in the laboratory. Irrespective of the sources, the powders exist as a polydisperse form. The pharmaceutical industry prefers powders of monodisperse or at least

within the narrow size distribution. The differences in the sizes may influence mechanical work, surface reactivity, taste, mixing, filtration, conductivity, etc. For the purpose of reproducibility, raw materials, intermediates and finished products are evaluated for the size distribution as the methods of quality control and quality assurance. It is necessary to calculate the specific surface of the drug which influences the bioavailability. Given such an importance, the Indian Pharmacopoeia has attempted to define the powders from coarse to fine and known as standards. For explaining the designations, standards of sieves are also prescribed, namely nominal mesh aperture size, sieve number, etc. Several types of sieves are fabricated as per the compendia specifications and commercially available as standard sieves.

Size separation operation is handled in two ways: standardisation of particle size and the second is the separation of sizes on industrial scale. Separate equipment are developed for the above two purposes. Sieve shaker and Alpine jet sieves are the first category. Several industrial scale sieve designs are available, namely shaking screen and Rotex screen. These are mechanical shakers and also included different modes of motion: namely agitation, brushing, and centrifugation to aid separation. A continuous monitoring of the particle size distribution can guarantee a constant product quality. Size separation is also designed based on fluid velocity of particles under the influence of centrifugal force. Cyclone separator and air separator belong to this category. Sedimentation and settling behaviour of particles are taken advantage and utilized for size separation. These are known as classifiers and thickners. Further, elutriation methods are also explored for size separation, but the ultimate purpose is different. Based on these developments, the final choice of equipment depends on the feed material, nature of finished product, facilitates available, in addition to cost considerations.

Glossary of Symbols

ρ = Density of fluid, kg/m^3.
η = Viscosity of the medium, Pa.s.
ρ_s = Density of the particle, kg/m^3.
D = Diameter of the particles, m^3.
g = Acceleration due to gravity, m/s^2.
U = Terminal settling velocity, m^3/s.

QUESTION BANK

Each question carries one mark

Note : Encircle the alphabet which corresponds to the single best response.

1. Size classification is also known in one of the following terms.
   A. Size analysis B. Size distribution
   C. Size reduction D. Size separation
2. Size separation is NOT based on one of the following properties.
   A. Particle density B. Particle shape
   C. Particle size D. Particle texture
3. Which one of the screens is used for size separation of big and heavy particles?
   A. Bar screens B. Bolting cloth sieves
   C. Punched plate screens D. Woven wire screens
4. Which one of the screens is attached to the hum-mur screens?
   A. Bar screens B. Cloth sieves
   C. Punched screens D. Woven wire screens
5. Which one of the following indicates the nominal size of aperture?
   A. Area of mesh as percentage
   B. Distance between two adjacent wires
   C. Number of meshes per linear length
   D. Wire having specified diameter that gives suitable aperture
6. During size separation, movement of particles can be enhanced by one of the following modes.
   A. Agitation B. Attrition
   C. Gravitation D. Mixing
7. Brushing method hastens the movement of one of the following materials.
   A. Coarse materials B. Dry materials
   C. Light materials D. Sticky materials
8. Flywheel is used to enhance the motion of particles by one of the following modes.
   A. Brushing mode B. Centrifugal mode
   C. Gyration mode D. Oscillation mode
9. Which equipment is used for sieve analysis?
   A. Alpine airjet sieve B. Cyclone separator
   C. Rotex screen D. Shaking screen
10. Fluidised state is NOT used in one of the following equipment.
    A. Air separator B. Alpine sieve
    C. Cyclone separator D. Rotex screen

11. Which is the disadvantage of the sieve shaker method?
    A. Attrition B. Capacity limited
    C. Expensive equipment D. Tedious
12. In cyclone separator, the separation depends on:
    A. Density and shape B. Shape and surface area
    C. Size and density D. Surface texture and size
13. In air separator, centrifugal force for circulation of air is applied by one of the following ways.
    A. Applying vacuum B. Atomizing air
    C. Pumping D. Rotating blades
14. Which is the term used to describe the materials that remains on the given screening surface?
    A Medium size material B. Minus material
    C. Neutral material D. Plus material
15. Which one of the following aids in size separation of sieve shaker machine?
    A. Agitation B. Brushing
    C. Centrifugal force D. Shearing force
16. Which is the disadvantage of Alpine airjet sieve method?
    A. Mesh gets blocked
    B. Method does not give reproducible results
    C. Not suitable for fine powder
    D. Method is tedious
17. Which are the following forces used in cyclone separator for size separation of particles?
    A. Adhesive forces B. Centrifugal forces
    C. Cohesive forces D. Shearing forces
18. A screen that sharply separates the feed mixture is called:
    A. Actual screen B. Ideal screen
    C. Real screen D. Virtual screen
19. Choose one of the following statements does NOT suit to sieve shaker.
    A. Apertures get clogged
    B. Attrition causing size reduction
    C. Lower limit of particle size is 50 μm
    D. Method is tedius
20. Choose the equipment in which filtering period and shaking period are alternatively observed.
    A. Air separation B. Bag filter
    C. Cyclone filter D. Borrclone

21. What is the process used for separating the light and heavy particles using a vertically directed stream of liquid?
    A. Centrifugation B. Elutriation
    C. Filtration D. Levigation

Each question carries 2 marks

1. Name the standards of screens used in pharmaceutical practice.
2. What are standard sieves?
3. Differentiate ideal and actual screens.
4. List the specifications and standards for sieves.
5. What are various grades of coarse powders? Define them.
6. Give the classification of fine powders with definitions.
7. What are the advantages of expressing sieves by a sieve number over the nominal size of aperture?
8. What are the uses of screen analysis? How is it expressed?
9. List the methods of sieve analysis used for testing the powders. Give their relative advantages.
10. What is the difference between free settling and hindered settling?
11. State the term 'elutriation'. Explain its applications and advantages.
12. What is the difference between static and moving liquid methods of elutriation?
13. Suggest the use of hydraulic classifiers in the size separation.
14. Suggest the methods of size separation in wet materials.
15. Suggest a method of size separation of corrosive materials.
16. What is the difference between sifting and shifting?

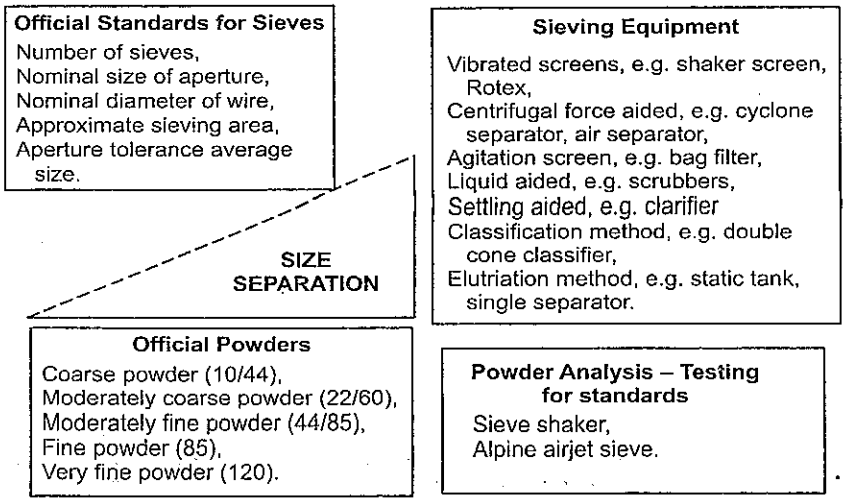
Each question carries 5 marks

1. Explain the working of a cyclone separator and its usefulness.
2. Describe the method of size separation using the Rotex shaker screen.
3. Explain various grades of powders official in pharmacopœia.
4. Give details about the various standards fixed by the pharmacopœia for sieves.
5. Describe the specifications of standard sieves as per IP.
6. Explain the concept of settling behaviour using water with a suitable example.
7. Explain the behaviour of slurry setting of thickeners with a suitable diagram.
8. Describe the principle, construction and working of a double cone classifier with the help of suitable diagram.
9. Explain the methods of size separation using water.
10. Explain the methods of separation of particles in a powder using air as a medium.

11. Explain the principles of sedimentation of particles using liquid as a medium.
12. Explain the specific uses and applications of a scrubber. Draw the sketch of the equipment.
13. List the critical quality attributes for size separation operation and highlight their importance in the performance of the product.

Each question carries 10 marks

1. Describe one industrial method for size separation of a powder and its applications.



MINDMAP OF SIZE SEPARTION OPERATION

CHAPTER **5**

Flow of Heat

Mechanisms of Heat Flow
Conduction
Convection
Radiation
Equipment—Heat Exchangers and Heat Interchanges
Steam as a Heating Medium
Steam Production—Utilization
Steam Traps

LEARNING OBJECTIVES

After reading this chapter, the reader should be able to:

- Appreciate the concept of heat flow and associated parameters.
- Understand the mechanisms of heat flow with general principles.
- Explain the application of Fourier law in the conduction of heat through the metal wall, composite walls and cylindrical pipe, including the application of thermal conductivity coefficient.
- Describe the flow of heat and heat transfer coefficient through the metal wall by forced convection and natural convection.
- Explain the process of heat transfer by radiation and the evaluation of energy transfer in black body and grey body.
- Describe the heat transfer equipment and types with construction, working and uses.
- Highlight the use of steam with its characteristics with special reference to the type and nature of steam is used as a heating medium.
- Explain the steam production, steam utilization along the use of steam straps, foam separators for obtaining heating efficiency.

Flow of heat is considered as a unit operation in which heat energy is transferred from a region of higher temperature to a region of lower temperature.

Heat is a form of energy. According to the principles of thermodynamics, whenever a physical or chemical transformation occurs, heat flows into or leaves the system.

A number of sources of heat is used for industrial scale operations. Steam and electric power are the chief sources to transfer heat. It is essential to convey steam without any losses to the apparatus in which it is used. The study of heat transfer processes helps in designing the plant efficiently and economically.

Applications

A few areas of relevance to pharmaceutical engineering are enumerated here.

Evaporation : Heat is supplied in order to convert a liquid (vehicle) into a vapour, which is subsequently removed. This process is used for preparing vegetable extracts. A construction similar to shell-and-tube heat exchanger is employed in evaporators. The heat flow can be quantified so as to estimate the efficiency of the process.

Distillation : Heat is supplied to a liquid mixture for converting the liquid into vapour so that the individual vapour components are condensed at another place. In case of steam distillation, steam will be in direct contact with the material.

Drying : In the production of tablets, heat is passed through a carrier gas over a bed of wet solid mass for achieving drying. In case of spray drying, heat is supplied to the solutions and suspensions (as in case of production of milk products).

Crystallisation : Saturated solution is heated to bring about super-saturation, which promotes the crystallisation of drugs. On the other hand, removal of heat (cooling) from a saturated solution also facilitates crystallisation, as in case of purification of bulk drugs.

Sterilization : For the sterilization of pharmaceuticals, autoclaves are used with steam as a heating medium. Dry heat is used for the sterilization of glass apparatus and other containers.

In addition, a number of other processes, such as boiling, exsiccation, sublimation and fusion, also use heat.

In a laboratory setup, number of equipment involving heat are used. E.g. air-ovens, incubators, dryers and refrigerators. On industrial scale, equipment are used for applying heat, removing heat and preventing heat loss. Heat transfer in many systems occurs as a steady state, i.e. temperature does not change with time at any point of the process. Unsteady state is also commonly observed when warming or cooling is desirable, in which thermal capacity is important. Analysis of unsteady state is a complex process. The basic principles involved in heat transfer are understood properly for the maintenance and efficient working of the equipment.

MECHANISMS OF HEAT FLOW

Heat flows from a region of high temperature to a region of low temperature. Heat may flow by one or more of the three basic mechanisms.

Conduction

Conduction is a process in which heat flow in a body is achieved by the transfer of the momentum of individual atoms or molecules without mixing.

For example, flow of heat through the metal shell of a boiler takes place by conduction as far as solid wall or shell is considered. No mixing is involved. Conduction is limited to solids and fluids whose movement is restricted. The flow of heat depends on the transfer of vibrational energy from one molecule to another, and in case of metals, the movement of free electrons, such that no appreciable displace of matter occur. Conduction in the bulk of fluids is normally overshadowed by convection, but it assumes great importance at fluid boundaries.

Convection

Convection is a process in which heat flow is achieved by actual mixing of warmer portions with cooler portions of the same material.

For example, heating of water by a hot surface (coil type water heater) is mainly by convection. Convection is restricted to the flow of heat in fluids (i.e. liquids and gases). Convection currents of air are set up almost daily in the atmosphere. These are responsible for winds, land and sea breezes, ocean currents, etc. Buoyancy forces are induced by variations in the density of the fluid caused by differences in temperature.

Radiation

Radiation is a energy transfer process in which heat flows through space by means of electromagnetic waves.

For example, a black surface absorbs most of the radiation received by it Simultaneously the absorbed energy is quantitatively transferred into heat. Fused quartz transmits all the radiation that strikes it, while a polished opaque surface or mirror will reflect most of the radiation that strikes it. Solar water heaters, solar cookers, microwave ovens, microwave cookers, sonicator baths, etc. are a few examples in which radiation is utilized for producing heat. Radiation is rare in solids, but examples are found among glasses and plastics.

In general, these mechanisms may operate simultaneously. For example, in ovens hot air is circulated by fan, so as to transfer heat by forced convection. Simultaneously, heat is transferred by conduction from the shelf to the material in contact. Heat also radiates from hot walls of the oven.

CONDUCTION

Heat can flow only when there is a temperature gradient, i.e. heat flows from a hot surface to a cold surface. The rate of conduction through solids can be studied easily, since it is the sole phenomenon. The basic law of heat transfer by conduction can be written in the form of a rate equation as follows:

$$\text{Rate} = \frac{\text{driving force}}{\text{resistance}} \qquad ...(1)$$

The driving force is the temperature drop across the solid surfaces. The greater the temperature drop, the greater will be the rate of heat flow.

The flow of heat will also depend on the conductivity of the materials through which it is flowing. For example, conduction of heat is faster through an iron rod than through a wooden log. This factor is represented through an iron rod than through a wooden log. This factor is represented by the term resistance, which can be quantitatively expressed by Fourier's law.

$$\text{Resistance} = \frac{\text{thickness of the surface (m)}}{\text{mean proportionality constant (W/m.K)}}$$

$$= \frac{L}{k_m A} \qquad ...(2)$$

Equation (2) for resistance can be obtained from the Fourier's law.

Fourier's Law—Conduction of Heat through a Metal Wall

Fourier's law states that the rate of heat flow through a uniform material is proportional to the area and the temperature drop and inversely proportional to the length of the path of flow.

The Fourier's law may be mathematically expressed as:

$$\text{Rate of heat flow} \propto \frac{\text{area (m}^2\text{)} \times \text{temperature difference } (\Delta t)}{\text{thickness (m)}}$$

$$q \propto \frac{A.\Delta t}{L}$$

or
$$q = \frac{k_m \,.\, A \,.\, \Delta t}{L} \qquad ...(3)$$

where k_m = mean proportionality constant, W/m·K.

Derivation : Fourier's law can be applied to a metal wall through which the conduction of heat is taking place (Figure 5-1). The characteristics are as follows.

Area of the wall = A, m^2

Thickness of the wall = L, m

Face of the wall (HH) is maintained at a uniform, definite and higher temperature = t_1, K

Face of the wall (CC) is maintained at a lower, but uniform temperature = t_2, K

The heat flow will be at right angles to the plane A and is assumed to be in a steady state. Consider a thin section of thickness dL at an intermediate point in the wall. This section is parallel to the plane, A. For this section, Fourier's law may be applied as given below.

$$\frac{dQ}{d\theta} = \frac{-k.A.dt}{dL} \qquad ...(4)$$

where Q = heat transferred, J
θ = time, s
k = proportionality constant, W/m·K
t = temperature, K

The constant, k, is a function of temperature, but independent of length. The '*minus*' sign indicates the decrease in temperature in the direction of flow. In equation (4), (dt/dL) represents the temperature gradient. For a steady state heat transfer, equation (4) changes to:

$$\frac{dQ}{d\theta} = \text{Constant} = q = \frac{-k.A.dt}{dL} \qquad ...(5)$$

where q = rate of heat transfer, J/s (or W)

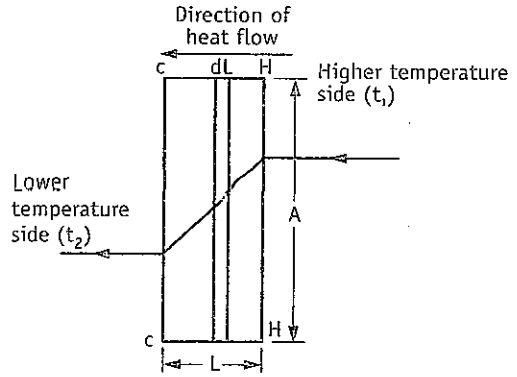


Figure 5-1. Heat transfer through a metal wall by conduction.

The temperature difference in the intermediate section is not known. But temperatures at the two faces of the wall are known. The area, A, may vary with L, but is independent of temperature. By separating the variables, equation (5) can be written as:

$$\frac{q.dL}{A} = -kdt \qquad ...(6)$$

Integrating equation (6) between the limits

$L = 0$ when $t = t_1$ and

$L = L$ (total thickness) when $t = t_2$,

gives: $$q\int_0^L \frac{dL}{A} = -\int_{t_1}^{t_2} kdt = -\int_{t_2}^{t_1} kdt$$

$$\frac{qL}{A} = k_m (t_1 - t_2) = k_m \Delta t \qquad ...(7)$$

Rearranging equation (7) gives:

$$q = \frac{-k.A.dt}{dL} \qquad ...(3)$$

where k_m = mean proportionality constant, W/m·K

In steady state heat transfer, 'q' remains constant. In equation (3), the term 'Δt' indicates the driving force. Equation (3) may be rearranged to obtain:

$$q = \frac{\Delta t}{L / k_m . A}$$

Comparing the above equation with rate expression [equation (1)] indicates that:

$$\text{Resistance} = \frac{L}{k_m . A} \qquad ...(2)$$

Fourier's law is thus used to define the resistance in quantitative terms.

Applications : Thermal conductivity is the reciprocal of thermal resistance. Thermal conductivity of a solid is expressed in terms of k as per equation (3).

The *coefficient of thermal conductivity* is the quantity of heat that flows across a unit surface area in unit time, when the temperature drop is unity.

The coefficient of thermal conductivity depends upon the material with which the body is made and upon its temperature. Thermal conductivities of some substances are given in Table 5-1. From Table 5-1, the following conclusions can be drawn.

- Thermal conductivities of liquids and gases are very small compared to most of the solids. In other words, the resistance offered by liquids and gases is high as far as the conduction is concerned.
- Metals have high conductivity, although values vary widely.

- Nonmetallic solids normally have low conductivities than metals. Carbon is an exception. Its relatively high conductivity and chemical inertness permits its wide use in heat exchangers.

TABLE 5-1
Thermal Conductivities of Some Metals

Materials	*Thermal conductivity, W/m·K*
Copper	379.0
Silver	410.0
Steel	43.0
Aluminium	24.2
Stainless steel	17.0
Carbon (graphite)	138.4
Glass (borosilicate)	1.0
Building bricks	0.69
Water	0.62
Air	0.03

- For the porous materials of metals, the overall conductivities lies between that of the homogenous solid and the air that permeates the structure.
- High resistant values lead to their wide use as heat insulators.
- In case of steam jacketed vessels, the kettle (inner surface) must have good conductivity so that maximum amount of heat passes from the steam to the contents. The high thermal conductivity of copper suggests that it is a suitable material for the construction of the kettle. At the same time, the metal used for jacket (outer surface) must have minimum conductivity to prevent loss of heat by conduction and radiation. The low thermal conductivity of iron suggests that it would be suitable material for the construction of the jacket. Such materials should be resistant to solvent or chemical action of liquid.

For the construction of evaporators and tubular heat exchangers thermal conductivity values are helpful. Thermal conductivity is very sensitive to changes in chemical composition and temperature and, therefore, the above values cannot be applied to all situations. The materials and their usefulness with respect to thermal conductivities are discussed in Chapter 12.

Compound Resistance in Series

Consider a flat wall constructed of a series of layers as in Figure 5-2. The characteristics are:

Thicknesses of the three layers = L_1, L_2 and L_3, m

Conductivities of materials of which layers are made

= k_1, k_2 and k_3, W/m·K

Area of the entire wall = A, m^2

Temperature drop across three layers = Δt_1, Δt_2, and Δt_3, K

Resistances of the three layers = R_1, R_2 and R_3

For the above descriptions, the total temperature drop may be written as:

$$\text{Driving force, } \Delta t = \Delta t_1 + \Delta t_2 + \Delta t_3 \qquad ...(8)$$

The rate of flow of heat through several resistances in series is exactly analogous to the current flowing through several electrical resistances in series. Therefore, the overall resistance (R) is equal to the sum of individual resistances.

$$R = R_1 + R_2 + R_3 \qquad ...(9)$$

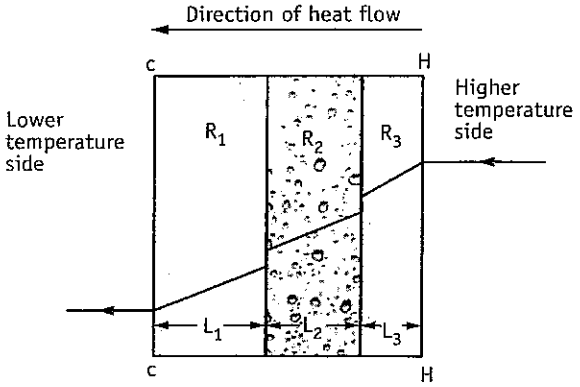


Figure 5-2. Flow of heat through several resistances arranged in series.

According to Fourier's law, individual resistances are described by equation (2). These are incorporated in equation (9) to get:

$$R = \frac{L_1}{k_1 A} + \frac{L_2}{k_2 A} + \frac{L_3}{k_3 A} \qquad ...(10)$$

Since entire heat must pass through the resistances in series, heat q can be written as:

$$q = q_1 + q_2 + q_3 \qquad ...(11)$$

Using the principles of conduction, the rate of heat transfer, q, may be expressed as:

$$q = \frac{\Delta t}{R_1 + R_2 + R_3} \qquad ...(12)$$

The contributions of temperature drops to the total temperature and individual resistances to the total resistance can be expressed mathematically as:

$$\Delta t : \Delta t_1 : \Delta t_2 : \Delta t_3 :: R : R_1 : R_2 : R_3 \qquad ...(13)$$

Heat Flow through A Cylinder—Conduction

In a heat exchanger, hot fluid or steam is passed through the circular pipe. The hot fluid transfers the heat to the inner surface of the pipe wall. Further heat transfer takes place by conduction through the pipe wall. Conduction is complicated because the area changes over which heat is transferred. The rate of heat transfer by conduction through a cylinder may be obtained as follows.

Consider a hollow cylinder as shown in Figure 5-3. The heat is flowing from inside to outside the cylinder. Consider a very thin cylinder at the centre of the pipe. The following characteristics may be enumerated.

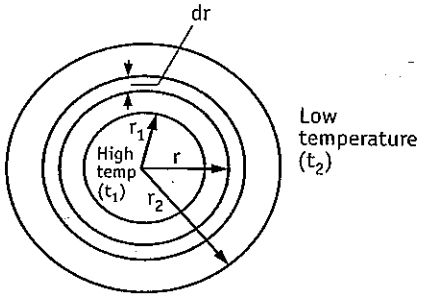


Figure 5-3. Flow of heat through thick-walled cylinder.

Mean thermal conductivity of material of cylinder = k_m, W/m·K

Temperature of the inside surface (higher) = t_1, K

Temperature of the outside surface (lower) = t_2, K

Radius of the thin cylinder = r, m

Thickness of the thin section = dr, m

Radius of the inner wall = r_1, m

Radius of the outer wall = r_2, m

Length of the hollow cylinder = N, m

The heat flow (in watts) is considered as parallel and the rate of heat transfer (q) can be written as:

$$q = -k \frac{dt}{dt} (2\pi rN) \qquad ...(14)$$

where $2\pi rN$ is the area of the heating surface, i.e. the interior of the cylin-

der. The mean surface area (A_m) may be written as circumference multiplied by length of cylinder.

Considering the variables such as radius and temperature, equation (14) is rearranged to obtain:

$$\frac{dr}{r} = \frac{-2\pi Nk}{q}$$

Integrating equation (15) within the limits of

$$r = r_1, \text{ when } t = t_1 \text{ and } r = r_2, \text{ when } t = t_2,$$

gives: $$\int_{r_1}^{r_2} \frac{dr}{r} = \frac{-2\pi N}{q} \int_{t_1}^{t_2} kdt = \frac{2\pi N}{q} \int_{t_2}^{t_1} kdt$$

$$\ln r_2 - \ln r_1 = (t_1 - t_2) \quad ; \quad q = \frac{2\pi N\, k_m\, (t_1 - t_2)}{\ln (r_2 / r_1)} \qquad ...(16)$$

Equation (16) can be used to calculate the rate of heat flow through a thick walled cylinder.

It is desirable to express the rate of heat flow in a more convenient form (similar to flat wall) as shown below.

$$q = \frac{\text{coefficient} \times \text{area} \times \text{temperature difference}}{\text{length of the metal layer}}$$

$$q = \frac{k_m \,.\, A_m \,.\, (t_1 - t_2)}{L} \qquad ...(17)$$

By equating the right hand-side terms in equations (16) and (17), the area (of surface) term may be obtained as:

$$\frac{A_m}{L} = \frac{2\pi N}{\ln (r_2 / r_1)}$$

Since L is the thickness, it is related to thickness of the tube, i.e. $(r_2 - r_1)$ of the cylinder. This value is substituted for L and rearranged to obtain A_m (mean area of a cylinder).

$$A_m = \frac{2\pi N\, (r_2 - r_1)}{\ln (r_2 / r_1)} \qquad ...(18)$$

A_m, area may be considered as $2\pi r_m N$. From equation (18), mean radius, r_m, may be written as:

$$r_m = \frac{(r_2 - r_1)}{\ln (r_2 / r_1)} = \frac{(r_2 - r_1)}{2.303 \log (r_2 / r_1)} \qquad ...(19)$$

In equation (19), the term, r_m, is called *logarithmic mean radius*. Logarithmic mean is less convenient than the arithmetic mean. The arithmetic mean is sufficiently accurate, if the tube is thin walled. This relationship is explained below.

- The arithmetic mean radius gives the result within 10 % of that obtained by equation (16). Logarithmic mean radius is used, if the value of $r_2/r_1 < 3.20$ (thick wall).
- The arithmetic mean diameter gives the results within 1 % of that obtained by equation (16). Logarithmic mean radius is used, if the value of $r_2/r_1 < 1.5$ (thin wall).

For most cases in practice, arithmetic mean radius is sufficiently accurate, if the cylinder is thin-walled. For thick walled tube, logarithmic mean radius has to be used.

Conduction Through Fluids

Conduction in liquids is usually small and this presents a considerable obstacle for heat transfer. Conductance in fluids is because of eddies setup by the changes in density with temperature, which is observed in the boiling of liquids (as in case of evaporation and distillation of liquids).

Conduction through fluids rarely occurs in practice, except when heat flows through thin films. In these cases, the thickness of the film is not exactly known. Therefore, equations described earlier cannot be applied. This difficulty can be overcome by the use of surface coefficient, which will be discussed later. If a body of fluid is large, both convection and conduction may prevail. This complicates the data analysis and fails to provide accurate predictions.

Comment 5-1. All metals having good electrical conductivity also will have good thermal conductivity. Explain.

Comment 5-2. What is the difference between log mean radius and arithmetic mean radius in conduction of heat?

CONVECTION

Convection is a process in which heat flow is achieved by actual mixing of warmer portions with cooler portions of the same material.

The heat transfer in fluid occurs on account of actual mixing of its layers.

Forced convection : It is defined as a heat transfer convection process *in which mixing of fluid may be obtained by the use of a stirrer or agitator* or pumping the fluid for recirculation. For example, in forced circulation evaporators, the evaporating liquid is forced through the tubes under pressure. Therefore forced convection is observed.

Natural convection : is defined as a heat transfer convection process in which mixing of fluid may be accomplished by the currents set up, when body of fluid is heated. For example, in pan evaporator, convection currents are set up in the evaporating liquid.

In general, fluid flow may be described as either laminar or turbulent. These create problems in the estimations. Some of them are as follows. When heat is passed through the tube, stagnant films determine the rate of heat transfer.

- When fluid exhibits viscous flow, the velocity is zero at the actual surface of the wall. It means that the layer of fluid adjacent to the wall acts as a stagnant film.
- A comparatively stagnant film can be observed even in turbulent flow. At the centre, the fluid is in turbulent flow, while at the surface the fluid exhibits viscous flow. A film of buffer layer oscillates between these types of flow.
- Sometimes, scales are deposited on the surface of the metal wall and heat must be conducted through the scales.
- When steam gives up latent heat, water will condense on the surface of the vessel (or tube). Again the heat must be conducted through this water film.

For heat transfer in a tube, heat must pass through the stagnant film by conduction. Hence, conductivity of these films is important. Normally, thermal conductivities of fluids are low. The conductivity of the stagnant film will be still less. For example, the thermal conductivity of water is less. A film of water has a resistance of about 500 times and that of air film is about 13,000 times greater than a copper sheet of the same thickness. Thus, the resistance offered by these films (though it is thin) is large for the heat flow. Beyond these films, the turbulence brings about rapid equalization of temperature.

Therefore, the resistance offered by the boundary film is of importance in the flow of heat, particularly in the evaporation process.

Forced Convection–Temperature Variation–Individual Heat Transfer Coefficients

Forced convection is a heat transfer convection process in which mixing of a fluid may be obtained by the use of a stirrer or agitator or pumping the fluid for recirculation.

Forced convection is obtained in some types of tube evaporators, wherein the evaporating liquid is forced through the tubes under pressure.

In a heat transfer process, the overall coefficient depends upon many variables. It is necessary to break them into individual parts. The temperature distribution across a column of fluid that is being heated (or cooled) is related to the velocity distribution across the same column of fluid.

Consider a case of heat flowing from a hot fluid through a metal wall into a cold fluid. At a specific point, the variation of temperature on each side of the metal wall is depicted in Figure 5-4. Several important facts are evident from Figure 5-4, as listed below.

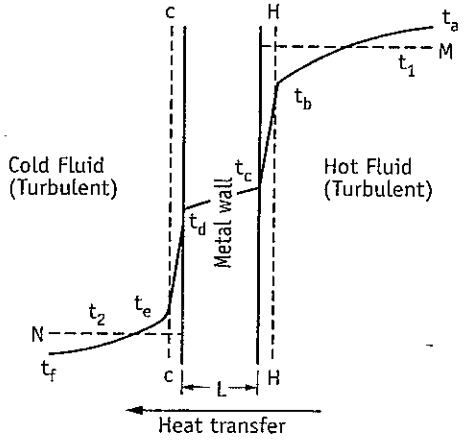


Figure 5-4. Temperature gradients in forced convection, while heat is flowing from a hot fluid to a cold fluid through a metal wall.

Metal wall : The characteristics are as follows:

(1) Dotted lines HH and CC represent the boundaries of the films in viscous flow on the hot and cold sides, respectively, on each side of the metal wall.

(2) The temperature gradient through the line $t_c t_d$ is caused by the flow of heat purely by conduction through the metal whose thermal conductivity is known.

(3) Metal wall thickness is L.

Hot fluid side : The characteristics are as follows.

(1) To the right of HH, the fluid is in turbulent flow on the hot side.

(2) t_a is the maximum temperature in the hot fluid.

(3) t_b is the temperature at the boundary on the hot side (turbulent and viscous flow junction).

(4) t_c is the temperature at the actual interface (between fluid and solid surface).

(5) Curve $t_a t_b t_c$ represents the temperature gradient from the bulk of the hot fluid to the metal wall. This is caused by the flow of heat in forced convection.

(6) t_1 is the average temperature on the hot fluid side represented by the line MM. In general, for heat transfer calculation, average temperature is important. This can be obtained by taking its temperature after mixing.

Cold fluid side : The characteristics are as follows.

(1) To the left of CC, the fluid is in turbulent flow on the cold side.

(2) t_f is the minimum temperature on the cold fluid.

(3) t_e is the temperature at the boundary on the cold side (viscous and turbulent flow junction).

(4) t_d is the temperature at the actual interface (between fluid and solid).

(5) Curve $t_d\ t_e\ t_f$ represents the temperature gradient from the metal wall to the bulk of the cold fluid. This is caused by the flow of heat in forced convection.

(6) t_2 is the average temperature on the cold fluid side represented by the line NN. In general, for heat transfer calculation average temperature is important. This can be obtained by taking its temperature after mixing.

Surface or film coefficients : In forced convection, the stagnant films (HH and CC) are of great importance in determining the rate of heat transfer. Though these films are thin, the resistance offered by them is large. Beyond these films, the turbulence brings about rapid equalization of temperature.

Film coefficient is the quantity of heat flowing through unit area of the stagnant film per unit drop in temperature.

It is the conductive capacity of the stagnant film for the transfer of heat.

It is difficult to determine the thermal resistances of fluid films, since thicknesses of the films cannot be known precisely. The thickness of the film depends not only on viscosity of the fluid, but also on the fluid circulation level (forced convection). Hence, the resistance offered by these films cannot be individually calculated. Therefore, indirect method of computation of surface coefficients is employed.

Let q watt (joules per second) of heat is flowing from hot fluid to cold one. Same heat must pass through stagnant fluid film on the hot side, through the metal wall and through the stagnant film on the cold side. Let the following be the characteristics.

Area of the metal wall on the hot side = A_1, m^2

Area of the metal wall on the cold side = A_2, m^2

Average area of the metal wall = A_m, m^2

Surface or film coefficient on the hot side : On the hot side, the surface coefficient, h_1, is defined as:

$$\text{Film coefficient on the hot side } (W/m^2.K) = \frac{\text{amount of heat flowing (W)}}{\text{area } (m^3) \times \text{difference in temperature (K)}}$$

$$h_1 = \frac{q}{A_1\ (t_1 - t_c)} \qquad ...(20)$$

From equations (20) and (7), it can be seen that surface coefficient (h_1) is analogous to the term, k/L for a metal wall. Since L/kA is the resistance term for metal wall, the term:

And, $\frac{1}{h_1 A_1}$ is known as thermal resistance on hot side.

The thermal resistance is due to the combined effect of the viscous film HH and the turbulent core. This resistance caused the difference in temperature, $t_a - t_b$.

Surface or film coefficient on the cold side : Film coefficient on the cold side can be written on similar lines as:

$$\text{Film coefficient on the cold side} = \frac{\text{amount of heat flowing}}{\text{area} \times \text{difference in temperature}}$$

$$h_2 = \frac{q}{A_2\ (t_d - t_2)} \qquad ...(21)$$

and, $\frac{1}{h_2 A_2}$ is known as thermal resistance on cold side.

Overall coefficient : In the over all heat transfer, three resistance terms are involved in series.

$\frac{1}{h_1 A_1}$ is the resistance on the hot fluid side.

$\frac{L}{k A_m}$ is the resistance of the metal wall.

$\frac{L}{h_2 A_2}$ is the resistance on the cold fluid side.

Applying the principle of compound resistance in series, the overall heat transfer may be written as:

$$q = \frac{\Delta t}{\frac{1}{h_1 A_1} + \frac{L}{k A_m} + \frac{1}{h_2 A_2}} \quad ...(22)$$

If both numerator and denominator of the right side of equation (22) are multiplied by A_1, equation (23) is obtained.

$$q = \frac{A_1 \Delta t}{\frac{1}{h_1} + \frac{LA_1}{k A_m} + \frac{A_1}{h_2 A_2}} \quad ...(23)$$

Then, the overall heat transfer coefficient U_1 (W/m^2·K) is defined by equation (24)

$$U_1 = \frac{1}{\frac{1}{h_1} + \frac{LA_1}{kA_m} + \frac{A_1}{h_2 A_2}} \quad ...(24)$$

If equation (24) is compared with equation (23), it is apparent that:

$$q = U_1 \Delta t A_1 \quad ...(25)$$

Equation (25) states that

$$\text{Rate of heat transfer} = \text{overall heat transfer coefficient} \times \text{area of the heating surface} \times \text{temperature drop} \quad ...(26)$$

For a tubular wall : The above derivation (equation 24) is based on the metal wall of thickness, L. This relationship may be extended to a tubular metal wall. The heat coefficients may be written in terms of diameter (metre), since area is proportional to the corresponding tube diameter. The overall heat transfer coefficient for a tubular metal wall may be written as:

$$U_1 = \frac{1}{\frac{1}{h_1} + \frac{LD_1}{kD_m} + \frac{D_1}{h_2 D_2}} \quad ...(27)$$

In some cases, one particular area is more convenient than the other. Suppose $h_2 >> h_1$, the (D_1/D_2h_2) becomes small in comparison to $(1/h_1)$. Similarly, resistance of the tube wall is also small in comparison with $(1/h_1)$. Hence, ratios (D_1/D_m) and (D_1/D_2) have very little significance and can be disregarded. Then, equation (27) becomes:

$$U_1 = \frac{1}{\frac{1}{h_1} + \frac{L}{k} + \frac{1}{h_2}} \quad ...(28)$$

Equation (28) can be used in cases of:

(a) thin walled tubes with larger diameter
(b) thin walled plates

In these cases, area A can be used for A_1, A_m and A_2, since errors will be negligible. In such cases,

$$U_1 = U_m = U_2 \quad ...(29)$$

When h_1 is very small compared to h^2 and (L/k), $(1/h_1)$ will be larger. Therefore, these two terms in the denominator are disregarded. Then

$$U_1 = h_1 \quad ...(30)$$

Thus, rate of heat flow from one fluid to another through the retaining wall can be simplified. Hence, numerical value of surface coefficients can be predicted easily.

Factors influencing film coefficients : Several factors influence the surface film coefficients. However, the factors that are widely applied in practice are a few with reference to the processing conditions. These are:

- Thermal conductivity of the liquid
- Specific heat of the film
- Density of the liquid
- Turbulence of the fluid
- Thickness of the film

If the films are thin, their resistances will be reduced. This can be achieved by increasing the speed of the steam on one side and the speed of liquid on other side.

Fluids in Natural Convection

Natural convection is defined as a heat transfer convection process in which a fluid is heated, the currents set up cause mixing of fluid.

The mechanism of natural convection is depicted in Figure 5-5. Consider a case of single horizontal cylinder. A large volume of fluid is present surrounding the cylinder. When a fluid is in contact with a hot surface, the fluid that is immediately adjacent to the tube absorbs heat. The temperature of this part of the fluid increases, which in turn decreases the density. As a result, the fluid rises from the surface and is replaced by the cold fluid. This process continues thereby effecting the mixing of hot and cold fluids.

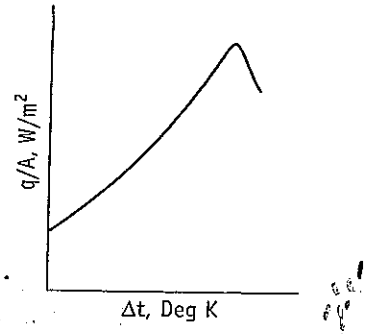


Figure 5-5. Mechanism of heat transfer in natural convection.

Fluid circulation caused by changes in the densities due to temperature differences in the fluid is termed as natural convection.

Fluid circulation also changes with:

- geometry of the system, i.e. size and arrangement of heating surface,
- shape of the vessel in which the fluid is enclosed.

The physical properties of the system are individually evaluated at the mean film temperature. Generally, hot bodies lose heat to their surroundings both by radiation and by convection. At lower temperature ranges, convection is more predominant, while radiation is important at higher temperature ranges. In practice, liquid film coefficients may vary from 10 to 200 depending on the arrangement of apparatus and the viscosity of the liquids.

Application : Natural convection is observed when extracts are evaporated in open pans.

Changes in Fluids during Heat Transfer

In heat transfer by convection, two liquids are involved. The hot liquid gives heat, while the cold liquid receives it. Each liquid undergoes changes during heat transfer. Steam condenses to give heat, while the cold liquid boils.

Hot liquid–condensing of vapour : Steam gives its heat of vaporisation during condensation. This heat is transferred to the cold liquid through a metal wall.

In a heater, steam is passed through the tubes or outside the tubes. In each case, the metal surface of the tube gets heated up. While transmitting heat to a metal surface, the saturated vapour condenses into two distinct forms based on the nature of wetting of the metal surface. These are as follows.

Film type condensation : In this type, the condensed liquid wets the surface on which it is condensing and forms a continuous film of condensate.

If condensation is occurring on the outside surface of a horizontal metal tube (a very common case), this film of condensate drops off beneath the tube. If the tube is vertical, then it runs down the whole length and drops off from the edge. Generally, smooth and clean surfaces tend to form film type. For film type condensation the film coefficients are low. Equations have been proposed for heat transfer calculations.

Drop-wise condensation : In this type, the condensed liquid collects as drops that may range from microscopic size up to drops that are seen with the naked eye.

If the condensed liquid does not wet the surface, the drops grow and then fall off the surface, leaving an apparent bare area on which new drops form. Normally, oily or greasy surfaces tend to induce drop-wise condensation. The coefficients for drop-wise condensation may be double or more than double that of film type under identical conditions. It is difficult to estimate the coefficients of heat transfer for drop-wise condensation.

In general, the film coefficient between condensing vapour and metal wall increases with increasing temperature of vapour. Film coefficients decrease with increasing temperature drop. When steam is employed as a source of heat, it is necessary to remove non-condensable gases. Other-wise, they reduce the film coefficients, because of their accumulation.

Cold liquid–boiling of liquids : When heat is supplied to a liquid, it boils and the vapour pressure increases. This process continues until the vapour pressure is equal to the atmospheric pressure. At this stage, the temperature of the liquid remains constant, which is known as boiling point. Generally, heat is supplied to a liquid through a heater by passing steam.

Consider a horizontal tube, which is immersed in a pool of pure liquid. Steam is passed through the tube. The heat transfer depends on the differences in temperatures on each side of the tube wall. The relationship between temperature differences and heat transfer coefficients in liquids (boiling outside the horizontal tube) is shown in Figure 5-6. Δt may be defined as:

Δt = tube wall temperature–saturated temperature of liquid (= vapour pressure in spaces)

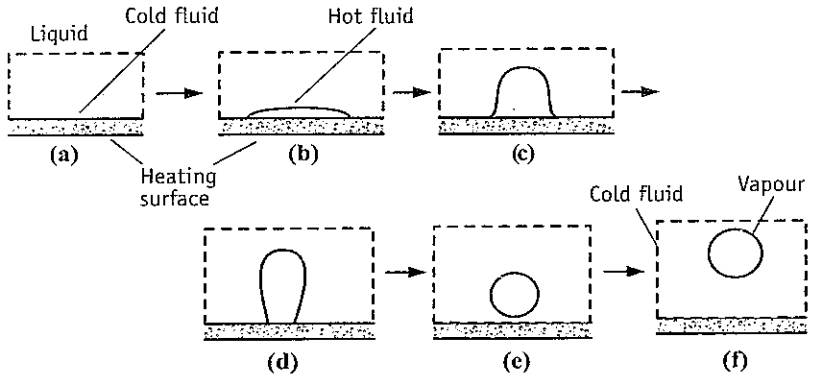


Figure 5-6. *Effect of temperature difference on the behaviour of a liquid boiling outside the horizontal tube.*

The following conclusions may be drawn from Figure 5-6.

(1) If Δt is very small, the rate of heat transfer (q/A) is not much. Hence, liquid doesn't boil.

(2) If Δt is increased, the rate of heat transfer (q/A) will be increased, because heat transfer coefficient increases rapidly. The mechanism is as follows. The heated liquid at the wall forms bubbles of vapour and gets detached from the surface. These vapour bubbles rise through the liquid. This type of boiling is called *nucleate boiling*. The cold fluid now wets the tube wall. Thus bubbles produce a series of currents, which have a stirring effect.

(3) If Δt is increased further, the surface temperature increases continuously up to a point, where the heat transfer coefficient reaches a maximum. This temperature is known as *critical* Δt. At this stage, the bubbles begin to coalesce into a continuous film of vapour, which insulates the tube.

(4) Beyond critical Δt, further increase in Δt leads to lowering of heat transfer coefficients rapidly. The continuous film of vapour insulates the tube, thereby the effective Δt fails to increase. Thus rate of heat transfer is decreased.

For some organic liquids, the heat transfer coefficient may decrease rather slowly after critical Δt. Therefore, maximum heat flux may occur at higher Δt than the maximum coefficient. The factors influencing heat transfer in boiling of liquids are:

- roughness of the tube
- type of roughness
- tendency of liquid to wet the tube
- difference in densities between bubble and liquid

There is no equation which can establish a relationship between coefficient and other factors. This is due to the diverse nature of apparatus (shape and size) and varying speeds of circulation.

Modes of Feed–Heat Transfer

Heat transfer by convection is involved between two liquids. The differences in the modes of feeding largely determine the efficiency of a heat process.

Parallel heat flow–Variation in temperature : Heat transfer across a metal surface from a hot fluid to a cold fluid depends on the temperature gradient (Δt). Generally, it is assumed to be constant for all parts of heating surface.

When the hot fluid and the cold fluid enter the apparatus from the same end, the flow is parallel to each other. This arrangement is known as *parallel flow*.

Consider a heat interchanger. The temperature of the hot fluid inside a pipe decreases from T_1 to T_2 by transferring heat to a cold fluid outside the

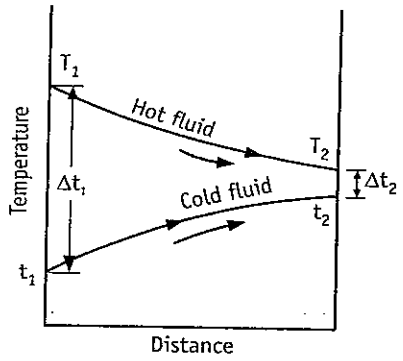


Figure 5-7. Temperature difference in parallel-current heat flow.

pipe. As a result, the cold fluid temperature is increased from t_1 to t_2. This condition is represented in Figure 5-7.

The temperature-drop at the left-end is much greater than at the right-end. It means that heat transfer is faster at left-side than that of the right-side. These changes, as occurring in a small section of the pipe, can be considered for the whole length of the pipe. Mathematically, heat transfer in parallel flow of liquids can be written as:

$$dq = U.A.\Delta t \qquad ...(31)$$

Equation (31) is based on two assumptions. (a) The overall coefficient (U) is considered constant throughout the equipment. (b) The specific heat of each fluid is considered constant. Integrating equation (31) gives:

$$q = \frac{\Delta t_1 - \Delta t_2}{\ln \dfrac{\Delta t_1}{\Delta t_2}} \qquad ...(32)$$

where L = length of pipe. m ; a = area of the pipe, m^2

Comparing equation (32) with the general equation of heat transfer (equation 25) gives :

$$\Delta t_m = \frac{\Delta t_1 - \Delta t_2}{\ln \dfrac{\Delta t_1}{\Delta t_2}} \qquad ...(33)$$

Thus logarithmic mean temperature difference (Δt_m) is used. The total heating surface (A) is equal to aL. Heat transfer equation in parallel flow heat exchanger is:

$$q = UA\Delta t_m \qquad ...(34)$$

The logarithmic mean temperature difference is used to account varying temperature drop in parallel flow. If the temperature drop is nearly

equal ($\Delta t_1 \cong \Delta t_2$), then arithmetic average temperature (Δt_m) can be used, which is a general expression for heat transfer.

In parallel heat flow, the heating obtained per unit surface area is much less effective at the fluid exit point compared to it at the point of entrance of the apparatus.

Counter-current heat flow–temperature gradient : When the hot fluid is passed through one end of the apparatus while cold fluid is passed through the other end, fluids by pass each other in the opposite directions. This arrangement is known as *counter-current or counter-flow.*

The temperature gradients for the counter-current flow are shown in Figure 5-8. From the Figure 5-8, it can be concluded that the temperature drop along the length of the apparatus is nearly constant. In other words, amount of heat transfer per unit area is substantially same at both ends. The heating surface is nearly constant throughout the apparatus.

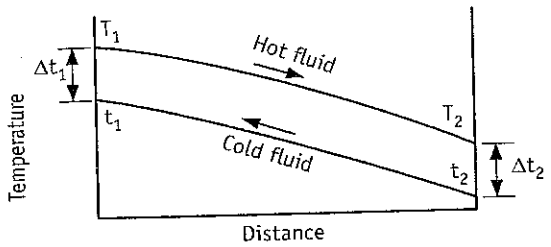


Figure 5-8. Temperature difference in counter-current heat flow.

In counter-current heat flow, the exit temperature of the hot fluid is considerably less than the exit temperature of the cold fluid. Hence a large proportion of the heat content of the hot fluid can be extracted for a given entrance temperature of the cold fluid.

If $\Delta t_1 \cong \Delta t_2$, temperature ($\Delta t$) can be taken as arithmetic average.

$$\Delta t_{ave} = \frac{\Delta t_1 + \Delta t_2}{2} \qquad ...(35)$$

The heat transfer equation for counter-current heat flow can be written as:

$$q = UA.\Delta t_{ave} \qquad ...(36)$$

Consider a case, where steam is transferring its heat to a colder body. Let the pressure difference in steam be constant. The temperature difference when steam is in a heat exchanger is shown in Figure 5-9.

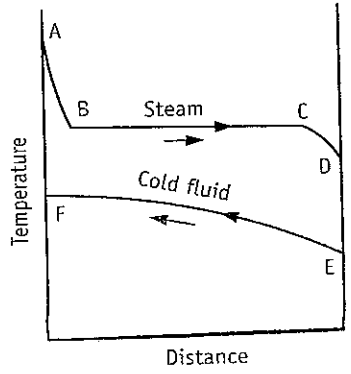


Figure 5-9. Temperature difference in counter-current heat flow in which steam is used as the heating medium.

Initially steam cools down to the condensing temperature as indicated by AB (Figure 5-9). Then condensation occurs at constant temperature (section BC), and may further be allowed to cool (section CD). Here large errors would be introduced, if AF and DE are taken for Δt_1 and Δt_2, respectively. Separate heat transfer calculations must be done for the three sections in Figure 5-9 and then are added.

Comment 5-3. Dimensional analysis is a useful tool for understanding heat flow of heat. Explain.

Comment 5-4. In forced convection, the heat transfer is due to molecular diffusion and eddies. True or false. Explain.

Comment 5-5. Differentiate between film coefficients and overall heat transfer coefficients.

RADIATION

Radiation is an energy transfer process in which heat is transferred through space by means of electromagnetic waves.

Thermal Radiation

Heat transfer by radiation is known as *thermal radiation.*

Radiation is effective across perfect vacuum and also through layers of air.

All solid bodies radiate energy when their temperatures are above the absolute zero. A solid surface emits radiant energy continuously and distributes over all wavelengths (i.e. from zero to infinity), although a major portion is concentrated within a relatively narrow range of wavelengths.

Heat transfer (thermal energy) is predominant as the temperature of the body increases. The amount and kind of thermal energy radiated increases rapidly with temperature. Thermal radiation usually occurs simultaneously with heat transfer by convection and conduction.

Various Forms of Emitters

Various forms of emitters used for the supply of radiant energy are given below:

Radiation source	*Wavelength*	*Applications*
IR lamp (1000 °C)	1 μm	High intensity radiation.
Ceramic rods and panels heated by gas or electricity (500 to 1300 °C).	2 to 4 μm	Pharmaceutical purposes, thermolabile substances.

Advantages : The radiation source corresponding to wavelengths from 0.8 to 400 mm is used for the thermal radiation. For most cases of industrial interest, the range is narrowed from 0.8 to 25 μm. Radiant energy

penetrates a short distance (1 to 2 μm) into materials. The heating effect occurs below the surface. For example, a film of solution can be dried by radiant heat, whereas surface skin retards the drying process in case of convection methods. Radiation assumes greater relevance at very high or very low temperatures and under circumstances in which other methods of heat transmission is suppressed.

Fundamental Concepts

Thermal radiation obeys same laws of light, namely—

(a) it travels in a straight line

(b) it may be reflected from the surface

Suppose a cold substance is placed in the sight of a hot body inside an enclosed space. The cold body intercept the radiation emitted by the hot body. The fraction of radiations falling on the body may be reflected, which is known as *reflectivity*, ρ. The fraction that is absorbed is known as *absorptivity*, α. The fraction that is transmitted is known as *transmissivity*, τ. The sum of these fractions must be unity or:

$$\alpha + \rho + \tau = 1$$

The following are a few observations.

- Most of the industrial solids are opaque and hence transmissivity is negligible.
- The absorptivity and reflectivity depends on the nature of surface and temperature.
- If a body absorbs all the incident radiations and its reflectivity is nil, then such a body is known as black body.
- Absorbed radiation is transferred into heat .
- A good absorber of heat (black body) is a good emitter of radiation.
- All real bodies do reflect a part of the incident radiation, but less than that of a black body.
- When the reflected radiation falls on other absorptive body, heat transfer takes place.

In practice, reflected and transmitted radiations usually fall on other absorptive bodies.

Black Body

Black body is defined as a body that radiates maximum possible amount of energy at a given temperature.

All solid bodies radiate energy at a temperature above the absolute zero, however, not at the same rate. For the purpose of heat transfer, a theoretic substance is proposed and designated as black body.

No physical substance is a perfect black body. The black matte surface approaches a black body, when visible light (rays) alone is considered. Light coloured substances deviate widely from it. Black surfaces are better emitters of heat radiation than polished surfaces. Further the term 'black' is nothing to do with the colour of the body. Similarly it has nothing to do with the amount of energy it radiates.

In theory, a black body is considered to be an enclosed space with a small (negligible) opening. The temperature in the enclosed space should be constant and uniform, because the amount of energy escaping through a small opening is negligible. In practice, a convenient black body is made from a tube of carbon. Both the ends are plugged, with a small hole at the centre of one end. When viewed through this small hole, the inside enclosed space (furnace) is considered as a black body, provided the temperature is uniform. Similarly all objects within the furnace (enclosed space) can be considered as black bodies.

A good absorber of heat is a good emitter too. Conversely a poor absorber is a poor emitter.

Rate of Radiation

The exchange of radiation is based on two laws.

1. Kirchoff's law
2. Stefan Boltzmann law

Kirchoff's law : It states that the ratio of emissive powder to the absorptive power is the same for all bodies that are in thermal equilibrium.

The necessary condition is the equilibrium of temperatures between the bodies. For a black body, absorptivity, $a = 1$, is the highest. In other words, the black body emits maximum amount of radiation.

Stefen Boltzmann law : This law states that the rate of energy emitted from a black body is proportional to the fourth powder of the absolute temperature, T.

Normally, hot bodies emit radiation. *Stefan-Boltzmann law* gives the total amount of radiation emitted by a *black body*.

$$q = bAT^4 \qquad ...(37)$$

where q = energy radiated per second, W (or J/s)

A = area of radiating surface, m^2

T = absolute temperature of the radiating surface, K

b = constant, $W/m^2 \cdot K^4$

According to equation (37), the rate of heating depends upon the temperature and surface area of the emitter. At the same time, it also depends

upon the absorption capacity of the material to be heated. There is no thermal equilibrium between the two bodies. Equation (37) permits the calculation of energy at each state (T_1 or T_2) for each body (black body and real body). The differences give the energy radiated.

For a black body, the value of b is 5.67×10^{-8} W/m^2·K^4. Actual bodies do not radiate as much as the black body. Therefore, equation (37) is modified for the *actual bodies*.

$$q = \varepsilon bAT^4 \qquad ...(38)$$

where ε is equal to the emissivity of the actual body. Emissivity may be expressed at the same temperature as:

$$\text{Emissivity, } \varepsilon = \frac{\text{energy emitted by actual body}}{\text{energy emitted by black body}} \qquad ...(39)$$

As per equation (39), emissivity is one for a black body. For actual bodies, ε is less than one, because a fraction of the radiation is absorbed, which appears as heat. The fraction of energy absorbed is denoted by absorptivity, α (other fractions are either reflected or transmitted).

A good absorber of heat is also a good emitter at a given temperature. If emissivity is equal to absorptivity ($\varepsilon = \alpha$), then a substance is considered as a black body. Since emissivity of a black body is 1, the absorptivity must be one. Therefore, the black body absorbs all the radiation falling on it.

Grey Body

Absorption of energy by a substance depends on its properties. Fairly high amount of energy will be absorbed by dark coloured, opaque and rough surface bodies. Least energy is absorbed by light coloured, transparent and smooth surfaced substances.

At a given temperature, the value of α varies somewhat with the wavelength of the radiation falling on it. This complicates the solving of problems in practice. Therefore, the concept of grey body has been introduced.

A *grey body* is defined as that body whose absorptivity is constant at all wavelengths of radiation, at a given temperature.

Consider a small cold body (real body) with a surface area of A and temperature of T_2 is completely surrounded by a hot black body at temperature T_1 (Figure 5-10). The amount of heat transferred in such a process is expressed by the Stefan law, which may be written as:

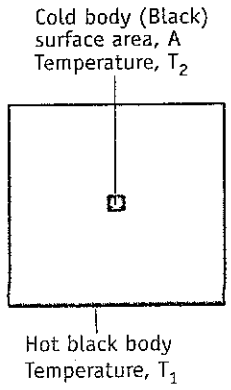


Figure 5-10. Heat transfer through radiation

$$q = bA\,(T_1^4 - T_2^4) \qquad ...(40)$$

Equation (40) assumes that all the heat radiated by a cooler body also falls on the hotter body.

Comment 5-6. Heat transfer is not possible in vacuum. Why?

Comment 5-7. Rusted iron rod has increased emissivity than polished iron rod. Explain.

Comment 5-8. Differentiate between 'black body' and 'grey body'.

EQUIPMENT

Heat Exchangers and Heat Interchangers

Most of the chemical and pharmaceutical industries employ a variety of heat transfer equipment. The materials to be heated may be liquids or gases and occasionally solids (which is a separate case by itself). The heating media may be a hot fluid or condensed steam. Some of the processes, which involve the heat transfer encountered in pharmacy are:

- preparation of starch paste (steam jacketed kettles) for granulation
- crystallization
- evaporation
- distillation

In industrial processes, heat energy is transferred by various methods. The principles, construction and working of equipment used for the transfer of heat energy are as follows:

Heat exchangers : *Heat exchangers* are the devices used for transferring heat from one fluid (hot gas or steam) to another fluid (liquid) through a metal wall.

Heat interchangers : *Heat interchangers* are the devices used for transferring heat from one liquid to another or from one gas to another gas through a metal wall.

The classification given above is vague and many times used interchangeably. Therefore, it is appropriate to call them as heat transfer equipment. Some of them are discussed in the following sections.

Heaters or Heat Exchangers

Heat exchangers are the devices used for transferring heat from one fluid (hot gas or steam) to another fluid (liquid) through a metal wall.

Some heat transfer (or heaters) equipment are:

(1) tubular heater (shell-and-tube heater)
(2) multipass heater
(3) two pass floating head heater

In heat exchangers, the film coefficients on the steam side are usually much larger than the film coefficients on the cold liquid side. Therefore, the overall heat transfer coefficients will be nearer to the cold liquid side (because it is smaller of the two coefficients). Hence, heat transfer becomes less. The efficiency can be improved by passing the liquid at a high velocity. As a result, the thickness and resistance of the liquid film decrease. Normally, the space outside the tubes is large, but steam velocity is low. Still heat exchangers are useful, because of the high values of the steam film coefficients.

Tubular heater (Shell-and-tube heater) : Shell-and-tube heater is the simplest form of a tubular heater. It is a single-pass tubular heater.

Construction : The construction of a simple tubular heater is shown in Figure 5-11. Tubular heater consists of a bundle of parallel tubes, which are relatively thin walled. The ends of these tubes are expanded into two tube sheets, B_1 and B_2. The bundle of tubes is enclosed in a cylindrical shell or casing, C, to which the tube-sheets are fitted. Many heaters have a cast iron shell.

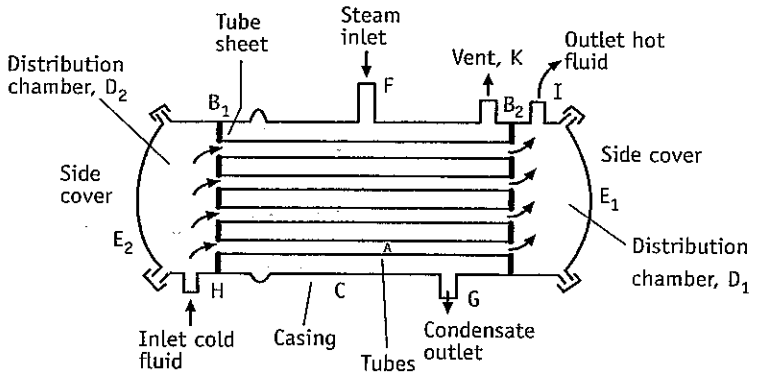


Figure 5-11. Construction of single-pass tubular heater.

Two distribution chambers, D_1 and D_2 are provided at each end of the casing C. Fluid inlet is provided to the distribution chamber D_2. The heated fluid outlet is provided to the distribution chamber D_1. Two covers, E_1 and E_2 are provided to close the distribution chambers from the sides. Steam or other vapour is introduced by a connection, F. Provisions are made for the escape of non-condensable vapour K and condensed vapour to drain at G.

Working : Steam or any vapour is introduced through a steam inlet F into the space surrounding the tubes. The steam flows down the tubes. In this process, the tubes get heated rapidly due to high values of steam film coefficients. The condensed vapour drains through condensate outlet at G.

Non-condensable gases, if any, escape through the vent K provided at the top of the casing.

The fluid to be heated is pumped through the cold fluid inlet H into distributing chamber D_2. The fluid flows up through the tubes. The steam and fluid are physically separated, but are in thermal contact through the thin tube walls. The fluid in the tubes get heated due to heat transfer by conduction through the metal wall, followed by stagnant layer and finally by convection. The total heat transfer is effected by single pass of fluid. Thus, the heated fluid reaches the distributing chamber D_1 and leaves through the hot fluid outlet, I.

In the sheet-and-tube heater, the cross sectional area of the tubes is larger. Hence, the velocity of the fluid inside the tubes is low.

Advantage : In single-pass tubular heater, large heating surface can be packed into a small volume.

Disadvantages : (1) The velocity of fluid flowing in these tubes is low, because of large cross-sectional area or larger surface.

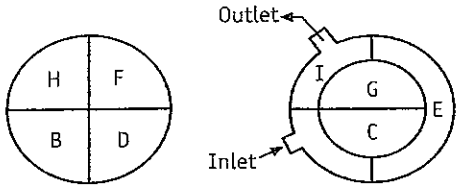
(2) The expansion of the tubes and shell takes place due to differences in temperatures. This may lead to the loosening of the tube sheets or buckle the tubes.

Multipass heater : In a multi-pass heater, the velocity of fluid can be increased. As a result, heat transfer coefficient also increases. As the name indicates, the liquid to be heated is passed through the tubes several times before leaving the equipment. This facilitates the effective heat transfer. Therefore, multipass tubular heaters are superior to the single-pass shell-and-tube heaters.

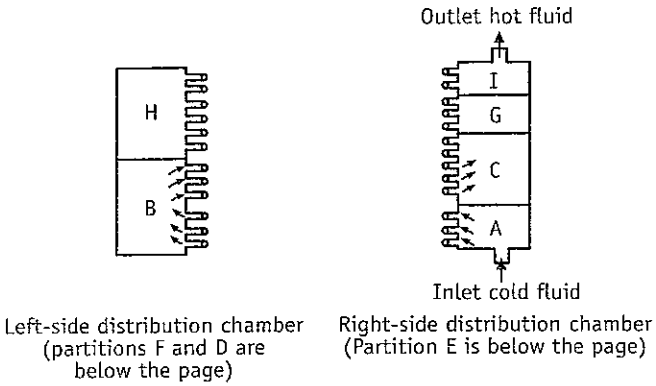
Construction : The construction of a multipass heater is same as tubular heater mentioned above, however, with some modifications (Figure 5-12).

Tubular multipass heater consists of a bundle of parallel tubes. The ends of these tubes are expanded into two tube sheets. The tubes bundle is wrapped in a cylindrical casing. Two distribution chambers are provided at each end of the casing. Since the heater is multipass, the same liquid has to flow through several tubes back and forth. In order to facilitate this process, distribution chambers are partitioned by means of baffles and their arrangements are different in the two chambers (Figure 5-12). The entrance and exit points of the fluid are arranged in the same distribution chamber (right side).

Working : Steam is introduced through the connection into the space surrounding the tubes. As the steam flows down, the tubes get heated. The condensed vapour is drained. Non-condensable gases, if any, escape through the vent provided at the top of the casing.



(a) When viewed from the side



(b) When viewed from the front

Figure 5-12. Construction of a multipass heater. In this figure, the modifications of distribution chambers and partitions are shown.

The fluid to be heated is pumped at high velocities into the right distribution chamber through the compartment, A. High velocity facilitates the effective heat transfer. In this construction, fluid is directed to enter only a fraction of the tubes by means of baffles placed in the distribution chamber.

The liquid enters compartment A and flows to the left into compartment B, back to the right to compartment, and so on in the same sequence of alphabetical order. During this process, fluid in the tubes get heated, due to heat transfer by conduction through the metal wall, followed by a stagnant layer and finally by convection. The net result is enhanced rate of heat transfer. Thus, the fluid passes back and forth through the several tubes and then leaves the equipment at I.

If the fluid is to be introduced at high velocities, pumping should be effective, which increases the cost of the power, though the cost of heater is low. Too low a velocity saves power for pumping, but needs a very large heater. *Therefore, a balanced approach should be worked out based on* economy.

Advantages : Multipass construction decreases the cross section of the fluid path, thereby increases the fluid velocity. Thus, multipass tubular heaters are superior to the single-pass shell-and-tube heaters.

Disadvantages : (1) The fabrication of a multipass heater is more complicated. (2) The pressure-drop through the apparatus is increased, because of enhanced velocity of fluid flow. (3) More number of exit and entrance points increase the friction losses. This increases the cost of pumping of fluid.

Floating-head two-pass heater : In floating-head two-pass heater, the ends of the tubes are structurally independent of the shell.

Construction : The construction of a two-pass floating head heater is shown in Figure 5-13. Its construction is the same as tubular heater with some modifications.

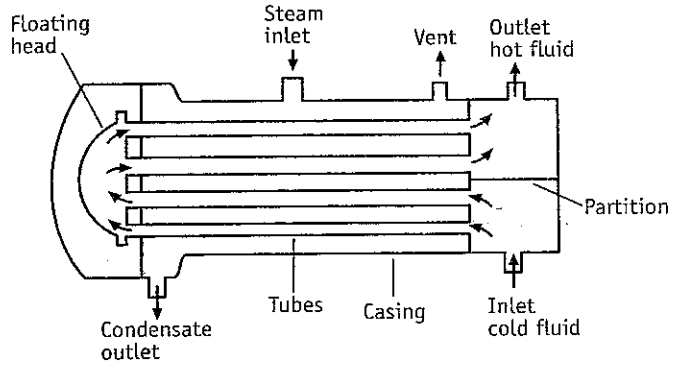


Figure 5-13. Construction of a two-pass floating head heater.

Two-pass floating head heater consists of a bundle of parallel tubes. These are enclosed in a shell (casing). The right-side of the distribution chamber is partitioned and fluid inlet and outlet are connected to the same chamber. The partition is such that both have equal number of tubes. On left-side, the distribution chamber is not connected to the casing. It is structurally independent, which is known as *floating head.* The other end of the tubes is embedded into the floating head. Steam or other vapour is introduced through inlet provided to the shell. Provisions are made for the escape of non-condensed vapour and an exit for the condensate.

Working : Steam is introduced through the inlet (Figure 5-13). As the steam flows down the tubes, they get heated. The condensed vapour escape through the bottom of the shell. Non-condensable gases, if any, escape through the vent at the top of the shell.

The fluid to be heated is introduced into the distribution chamber on right-side of the heater. The fluid flows through few tubes present in that part of the partition. The fluid reaches the floating head and changes direction. Now it passes back to the next part of the partition chamber on right-side. Therefore, the fluid flows twice through the tubes, i.e. two pass.

During this process, fluid in the tubes get heated, due to heat transfer by conduction through the metal wall, followed by a stagnant layer and finally by convection. Then the fluid leaves the outlet provided in the shell.

Advantages : In a shell-and-tube heat exchanger, tubes and shell may get expanded due to differences in temperature. Similarly contractions are also possible when heater is switched off. It leads to loosening of tube sheets or buckles the tubes. Therefore, constructing the tubes independent of the shell can prevent these effects. Such an arrangement is *floating head.*

Heat Interchangers

Heat interchangers are the devices used for transferring heat from one liquid to another or from one gas to another gas through a metal wall.

In heat interchangers, the heating medium is a hot liquid. The liquid to be heated is the cold liquid. In this case, the film coefficients both outside and inside the tubes are nearly of same magnitude. The value of the overall heat transfer coefficient, U, will be near that of the smaller of the two film coefficients. Hence, heat transfer is not efficient.

The film coefficients can be enhanced by increasing the velocity of flow. From the point of construction, it is difficult to increase the velocity of the hot fluid outside the tubes. However, surface area of contact can be increased, by introducing baffles in the construction. The increased surface area of contact enhances the coefficient. Thus the rate of heat transfer is enhanced. These principles are illustrated using different heat interchangers.

Baffles : Baffles consist of circular discs of sheet metal with one side cut away. These are perforated to receive tubes. To minimize leakage, the clearance between the baffles, shell and tubes should be small. The baffles are supported by one or more guide rods, which are fastened between the tube sheets by set-screws.

Working : Baffles are placed outside the tubes. These increase the velocity of liquid outside the tubes. Baffles make the liquid flow more or less right angles to the tubes, which creates more turbulence. This helps in reducing the resistance to heat transfer outside the tubes. Therefore, baffles constitute an important part in the heat transfer.

The construction of a liquid-to-liquid heat interchanger illustrates the principle of introducing the baffles into the equipment.

Liquid-to-liquid interchanger : The basic construction and working of any heat transfer equipment more or less remains the same. Only a few modifications are included.

Construction : The construction of a liquid-to-liquid heat interchanger is shown in Figure 5-14. Normally, tube sheets, spacer rods and baffles are

assembled first and then tubes are installed. The most important parts in the construction of the heat interchanger are the baffles.

Appropriate size of tube sheets is chosen for the fabrication. One or more guide rods are fixed to the tube sheets by means of set-screws. Baffles consist of circular discs of a metal sheet, with one side cut away. Baffles are placed at appropriate places using guide rods. The baffles are arranged with appropriate spacing using short sections of the same tubing as shown in Figure 5-14. Baffles have perforations through which tubes are inserted. The ends of tubes are expanded into the tube sheets. The above assembly is enclosed in a shell.

The shell has a provision for introducing the heating medium, hot fluid. The outlet for the fluid is at right-side top.

On each side of the tubes, two distribution chambers are provided. Left-side chamber contains an inlet for fluid to be heated. The outlet for the hot fluid (that is heated) is provided at the centre of the right-side distribution chamber.

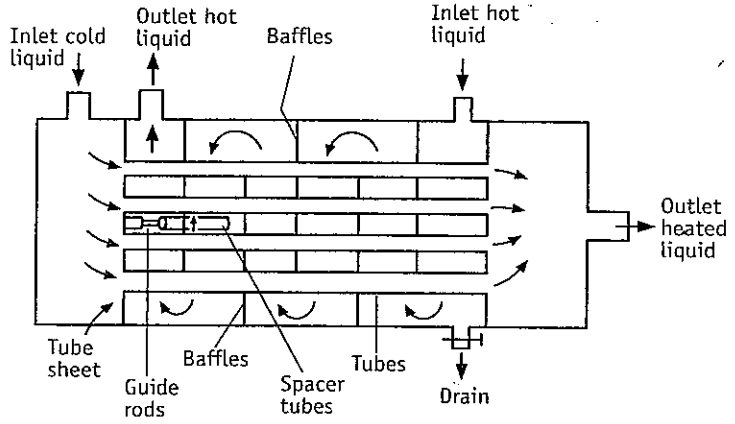


Figure 5-14. Construction of liquid-to-liquid heat interchanger.

Working : The hot fluid (heating medium) is pumped from the left-side top of the shell. The fluid flows outside the tubes and moves down directly to the bottom. Then, it changes the direction and rises again. This process is continued till it leaves the heater. Baffles increase the velocity of the liquid outside the tubes. Baffles also allow the fluid to flow more or less right angles to the tube, which creates more turbulence. These help in reducing the resistance to heat transfer outside the tubes. Baffles lengthen the path and decrease the cross-section of path of the cold fluid. The path of travel is as shown in Figure 5-14. The baffles get heated and provide greater surface area for heat transfer. Simultaneously, during the flow, the tubes also get heated. As a result, the film coefficient inside the tube also increases.

The liquid to be heated is pumped through the inlet provided on left-side distribution chamber. The liquid passes through the tubes and gets heated. The flow of liquid is single-pass. The heated liquid is collected from the right-hand side distribution chamber.

Advantages : In a liquid-to-liquid interchanger, heat transfer is rapid as the liquid:

(1) passes at high velocity outside the tubes.

(2) flows more or less at right angles to the tubes.

Double-pipe heat interchanger : In a liquid-to-liquid heat interchanger, the fluid to be heated is passed only once through the tubes before it gets discharged, i.e. single pass. The heat transfer in this case is not efficient. When a few tubes per pass are desirable, double pipe heat interchanger is employed.

Construction : The construction of a double-pipe heat interchanger is shown in Figure 5-15. In this, two pipes are used: one is inserted in the other. The inside pipe (or tube) is used for the pumping of cold liquid to be heated. The outer pipe acts as a jacket for the circulation of the hot liquid. All jacketed sections are inter-connected.

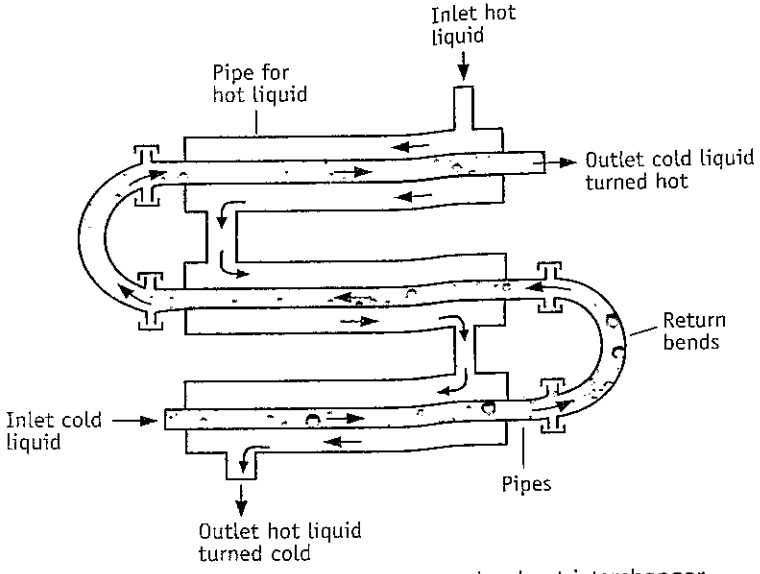


Figure 5-15. Construction of double-pipe heat interchanger.

Normally, the number of pipe sections is few. The length of the pipe is also less. Glass tube, standard iron pipe and graphite constructions are available. Standard metal pipes are assembled with standard return bends.

A proper number of such pipes are connected in parallel and stacked vertically. The pipes may have longitudinal fins on its outer surface.

Working : The hot liquid (heating medium) is pumped into the jacketed section. The hot fluid is circulated through the annular spaces between them and carried from one section to the next section. Finally it leaves the jacket. In this process the pipes get heated, while the hot fluid looses its temperature.

The liquid to be heated is pumped through the inlet provided at right side. The liquid gets heated up and flows through the bent tubes into the next section of the pipe. The liquid further gets heated. The same liquid continues to flow and finally leaves the interchanger through the exit point on the right side.

Uses : Double pipe heat interchanger is useful when not more than 0.9 to 1.4 m^2 square of surface is required.

Scraped-Surface Heat Exchanger

Principle : In this type of liquid-liquid heat exchanger, a spring-loaded scraper blade is included for enhancing the overall heat transfer coefficients. The scraper blade rotates at a certain speed and scrap the inside liquid surface layer of the inner tube, which is otherwise stagnant. This permits the replacement of existing liquid layers by a new portion of liquid. Thus exchange of heat is effective.

Construction : The construction of a scraped-surface heat exchanger is given in Figure 5-16. It consists of a double pipe construction: one is kept inside the other. The common sizes are 6 inches inside pipe and 8 inches outside pipe. In the inner tube, two or more spring-loaded scraper blades are attached longitudinally to a central shaft. The shaft is connected to a motor for allowing the blade to rotate. The other end of the blade reaches closer to the inner pipe wall. These double pipe units are commonly connected in series and arranged in double stands. Often, the system can employ jacket arrangement for maintaining temperature.

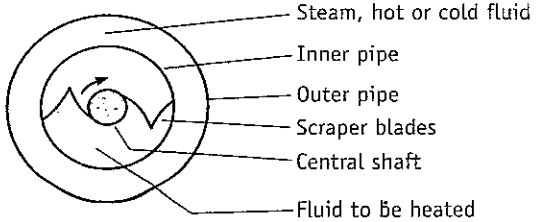


Figure 5-16. Scraped-surface heat exchanger.

Working : The heating medium (steam, hot or cold water) is passed through the outer tube. The viscous fluid to be heated is passed through the

inner tube at low velocity. Heat transfer takes place through the circulated surface by conduction and convection. The portion of liquid adjacent to the inner surface of the inner tube is stagnant. The shaft is allowed to rotate at a certain speed and scrape the inside surface of the inner tube. Any liquid that was previously on this surface is scraped and replaced by other liquid at that temperature. This permits the effective transfer of heat, but at unsteady state condition.

Uses : Scraped-surface exchangers are particularly suitable for heat transfer (cooling) in crystallization. Heat transfer is effective even with severe fouling, solvent extraction, high velocity fluids. This is possible because of spring-loaded scraped blade mechanism. These are used in the production of food products and other heat sensitive liquids (using high vacuum). It is used in paraffin wax plants.

Finned Tubes

The general heat transfer rate (q) equation in a heat exchanger is:

$$q = UA\,\Delta t$$

where U = overall heat transfer coefficient, $W/m^2.K$

A = area of the heating surface, m^2

Δt = difference in temperature on both sides of the tube, K

Consider the case of a heat exchanger in which air is present outside the tubes and steam is inside the tubes. Air gets heated due to heat transfer through the tube wall. The heat transfer coefficient on the steam side surface is very high, while it is extremely low on air-side. As a result, the overall coefficient, U, approximates that of the lower side, i.e. air-side.

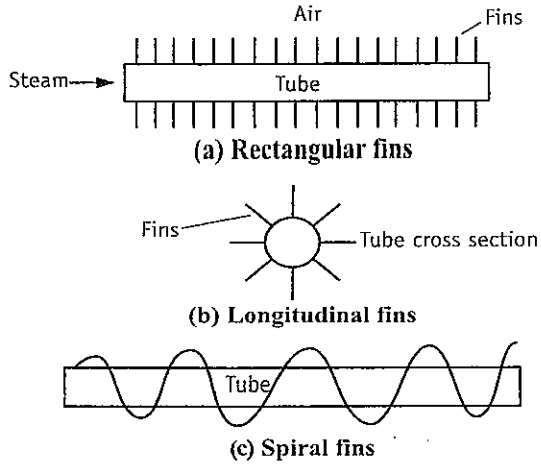


Figure 5-17. Variations in the arrangements of fins on tubes in a heat interchanger.

Since, U is decreased, the only way to increase q is to increase the surface area term, A, on the air-side.

As metals generally have high thermal conductivity, the temperature of the metal surface approximates to that of steam. Surface area of contact is enhanced by fixing fins on outside of the tubes, without putting more number of tubes in the heater.

Construction : A variety of fins are used as shown in Figure 5-17. Fins may be placed on the inner wall as well as on the outside of the tubes. Rectangular discs of a metal may be placed at right angles to the tubes (Figure 5-17a). Longitudinal fins are also employed (Figure 5-17b). Spiral fins may be attached to the tubes (Figure 5-17c).

Uses : Fins greatly reduce the size of the apparatus. They also increase the surface area of contact. This in turn enhances the rate of heat transfer in a heat exchanger. In double-pipe heat interchanger, fins are employed.

Heat insulation : The distribution of steam through the pipe can be reduced using heat insulators. The pipes should be lagged, i.e. covered with a layer of porous, poor conducting material such as kieselguhr, asbestos and glass wool.

Alternatively, several layers of aluminium foil can be applied for effective insulation. The surface of the foil prevents the radiation losses and air trapped between the layers minimizes convection losses.

Comment 5-9. What are the efficient techniques in enhancing the heat transfer in heat exchangers?

STEAM AS A HEATING MEDIUM

Steam is a vapour of water. Steam does not obey laws of perfect gases, until it is perfectly dry. Superheated steam (vapour) behaves more or less like a perfect gas. Steam has a high latent heat of condensation per unit weight and is therefore, very effective as a heating medium. Hence, steam is used on industrial scale. The temperature of the steam depends on the pressure. As the pressure increases the saturation temperature increases and vice versa, which results in higher sensible heat. When steam is used as heat medium, it is at saturation temperature, the heat given up will be its latent heat and a part of heat condenses. The temperature remains unchanged, i.e. saturation temperature remains same. When all the steam is condensed, temperature begins to fall and sensible heat starts liberating.

Characteristics of Steam

In general, gases and vapour are very bad conductors of heat and give up their heat very slowly. Liquids give up their heat much more quickly. Steam has several characteristics which makes it suitable as an important heating medium in pharmaceutical industry.

- Steam should be as dry as possible thereby heat losses can be minimized.
- Since the latent heat is the useful heat, steam should be used at the lowest pressure that will give a suitable temperature gradient.
- Steam should be pumped in its saturation temperature. Superheated steam should not be used.
- Steam should be replaced continuously so that the operation proceeds uninterrupted.
- Super-heating gives higher temperature, though it has little value in plant process. Super-heating prevents the condensation in steam lines.

Steps are taken during the production of steam, so that their characteristics are maintained.

Uses : Many pharmaceutical processes, namely evaporation, refrigeration, transportation, distillation, drying etc. require heating and hence steam can be used. Apart from these, several other uses are given below.

- During the manufacture of creams, the product is maintained at a temperature at 60 to 70 °C.
- During the manufacture of solutions, temperature of 80 to 90 °C is maintained for solubilisation of preservatives.
- Superheated steam is used to run steam engines economically.
- Steam is used for sterilization of pharmaceutical products.

Advantages of steam : Steam is having many advantages which have economic and technical considerations as mentioned below.

1. Raw material is water and available in large quantities.
2. Steam is easy to generate, distribute and control.
3. It is generally cheaper than the electricity.
4. It is clean, odourless and tasteless. Accidental contamination of the product is less likely to be serious.
5. It has high heat content (latent heat), which can quickly heat the materials.
6. Heat is given up at constant temperature, which is useful in controlling heating processes and in sterilization.

Disadvantages : Steam presents potential safety problems and necessitates the use of high strength pipes. This is particularly true in case of steam pressures upto three times higher than atmospheric pressure.

Heat Content of Steam

The flow of heat in the transformation of ice to steam is shown in Figure 5-18.

Sensible heat : *Sensible heat* is the heat that is utilized to increase the temperature of one kg of water from the freezing point (0 °C) to the temperature of formation of steam (100 °C), i.e. saturation temperature.

Sensible heat is also known as liquid heat. *Sensible heat* may be calculated using the following equation.

$$\text{Sensible heat} = \text{mass of water} \times \text{specific heat capacity} \times \text{temperature rise}$$

$$h = m\, S\Delta T \qquad \ldots(41)$$

$$= 1 \text{ kg} \times 4.2 \times (100 - 0) = 420 \text{ kJ}$$

For water, specific heat capacity = 4.2 kJ/kg.K, i.e. for one kg of water. The S value varies slightly with changes in the pressure and temperature.

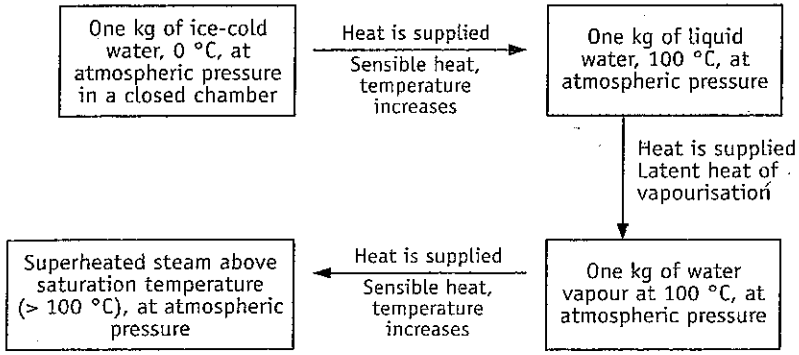


Figure 5-18. Sequence of events that occur, while heating the ice cold water to produce steam.

Latent heat of steam : *Latent heat of steam* is the heat required to convert one kg of liquid water at its boiling point (100 °C) or saturation temperature to one kg of water vapour, without changing the temperature.

Latent heat is known as *enthalpy*. The unit of heat is kJ/kg. Latent heat of steam is calculated using equation (42) at atmospheric pressure.

Latent heat of steam = mass of water × latent heat of vapourization

$$Q = mL \qquad \ldots(42)$$

For water, L is 2.26×10^6 J/kg. If the steam is fully dry, then :

Latent heat of steam, $Q = 1 \times 2.26 \times 10^6 = 2.26$ MJ/kg

When steam is condensed (gas to liquid), the latent heat is released, which is utilized for heating. The value of Q depends upon the pressure. It decreases with increase in pressure. The value of L depends on temperature and pressure. If the steam also contains liquid water, then the fraction of dryness of steam must also be included in the equation (42). If the dryness fraction of wet steam is q, then:

$$Q = mqL \quad ...(43)$$

Applications : Latent heat is the major portion of the total heat. It is the useful heat. Steam should be used at a lowest pressure that will give suitable temperature gradient. At critical pressure, the latent heat of vapourization is zero.

Wet steam : *Wet steam* is the steam in which liquid water is also present in a definite proportion.

Wet steam means that the evaporation of water is not complete and the whole of the latent heat has not been absorbed. Wet steam is expressed in percent of fraction, i.e. wetness fraction. It is mathematically expressed as:

$$\text{Wetness fraction} = \frac{\text{mass of liquid water in (moisture) in vapour}}{\text{total mass of water}} \quad ...(44)$$

Saturated steam : It is the steam at a temperature of boiling point of water (100 °C) at that pressure.

Application : Saturated steam should be used in heating the equipment.

Dry saturated steam : It is the steam that contains latent heat of energy of vapourization, i.e. full vapour. Liquid water is absent in the steam. At this state, the heat of vapourization is maximum, i.e. maximum heat content. The heat content is 2.26 MJ/kg. This steam is ideal for heating and sterilization. When heat is added to steam-water (wet steam) mixture, water is completely converted into steam.

Dry steam : Dry steam is the steam in which water is completely absent.

Dry fraction : It is the weight fraction of dry steam in a steam/water mixture. For example, if dry fraction is 0.5, only half of water has been converted into steam. The dryness fraction governs the latent heat content of the steam. At 0.5 fraction, the latent heat is half (2.26/2), i.e. 1.13 MJ.kg. It is the maximum when the dryness is one. Dryness is called the *quality of steam*.

Total heat of steam or enthalpy : It is the amount of heat absorbed by water from freezing point (0 °C) to saturation temperature (100 °C) plus the heat absorbed during evaporation.

Heat of steam (saturated steam) = latent heat + sensible heat

$$H_S = L + h \quad ...(45)$$

Superheated steam : It is the steam that is heated further even after complete conversion of water into vapour. When water is heated, the heat is utilized as latent heat and liquid water vapourizes. This process continues until liquid water is completely converted into vapour. When all

water is completely vapourized, further heating cannot be utilized as latent heat. Hence, such heat enters as a sensible heat. As a result, the temperature of vapour rises, but pressure remains same. Such a steam is known as *superheated steam*. That temperature is known as *superheated steam temperature*. Under these conditions, the volume of steam increases. In actual practice, the superheated steam is produced in a separate apparatus known as super-heater, so that it is out of contact with water from which it was formed.

Total heat content = heat content of the saturated steam – heat content of superheated steam

$$H_{total} = H_S + H_{sup} \quad ...(46)$$

Applications : Superheated steam is of little value, when steam is required as source of heat. Superheated steam is used to improve the economy of steam engines. A slight degree of superheat is of advantage to prevent condensation in the steam lines and is easily obtained by throttling so as to have a pressure in the boiler slightly higher than that of the steam mains.

Exhaust steam : Exhaust steam is often available as a byproduct from power plants. Exhaust steam usually has a saturation temperature ranging from 215 to 230 °F. Hence, it is useful for heating, only when the required delivery temperature is about 200 °F.

Process steam : This steam gives a temperature of 200 °F.

Specific volume of steam : It is the volume occupied by the steam per unit mass at a given temperature and pressure.

It is expressed in m^3/kg. It is the reciprocal of density of steam, kg/m^3. The volume occupied by one kg of steam is known as specific volume of steam. The specific volume of the steam decreases as the pressure increases, i.e. the molecules need less energy to expand and fill the available volume. At critical pressure, the steam occupies same volume as of water.

Steam table : Steam table lists different properties of steam and their values at different temperatures and pressures. Some of these properties are given below.

1. Pressure
2. Saturation temperature
3. Dryness fraction
4. Sensible heat
5. Latent heat
6. Superheat
7. Total heat
8. Specific volume
9. Entropy

There are two important steam tables, one in terms of absolute pressure and the other is in terms of temperature.

STEAM PRODUCTION — UTILIZATION

In a remote boiler house, steam generator is installed for producing the steam. Then it is supplied elsewhere in the plant to equipment. Hence, high strength pipes are employed. The pipes of lagged (insulated with bad-conducting material) to avoid heat loss and condensation in the pipes. Steam is produced at high pressure. It provides the driving force for distribution of steam. Expansion of high pressure steam to a low pressure zone at the plant will help to dry the steam. Steam generators are operated under the close supervision of a qualified and competent person.

Advantages of Steam Boiler

1. High pressure steam can be used to drive a turbine for generating electric power.
2. Low pressure exhaust steam is used for process-heating.
3. Central generation is more economical.
4. More steam is stored in a boiler, if high pressure is applied.
5. High pressure steam means high temperature.

Attachments of Steam to Process Equipment

The construction of equipment (vessel) with the facility of supplying steam is shown in Figure 5-19. The vessel is constructed using a suitable grade (strong) stainless steel with an acceptable thermal conductivity. It must be resistant to corrosion and be easily cleaned and sterilised. The outer surface of the jacket is made with material having poor thermal conductivity, so that heat loss to the environment is reduced.

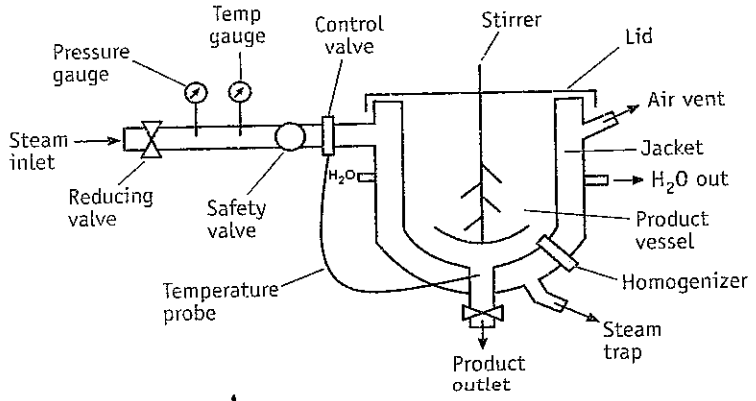


Figure 5-19. Process vessel with steam attachments and controls.

Steam is generated at high pressure and temperature (6-8 $\times$ 10^5 Pa and 160 to 170 °C), and suitably delivered to equipment at about 1.5-3.0 $\times$ 10^5 Pa and temperature of 110-135 °C. This usually gives a sufficient

temperature gradient to heat the product at the required rate, but reduces the chances of localised overheating.

Steam may be operated manually in small scale. In large equipment, it is controlled automatically via a control panel and electronic signal from a pressure gauge.

- A reduced valve is used to reduce and control/adjust the pressure at the desired level.
- The panel is continuously monitored the product temperature through a probe.
- When the control valve opens, steam enters the jacket and the product starts to heat up.
- The pressure and temperature gauges allow the monitoring and recording of steam properties.
- A safety valve is positioned before the control valve. It is set to open and direct steam from the installation, if the pressure reaches a value excess to that of the safe operating pressure of the system.

Working : When steam first enters the jacket surrounding the product, it contacts the cooler surface, condenses and releases latent heat, which is then transferred through various layers to the product. On condensing, steam contracts to a small volume and creates an area of lower pressure within the jacket into which more steam will then flow. Steam will therefore continue to enter the jacket to maintain the desired pressure until the product temperature reaches the steam temperature and no further condensation occurs. The stirrer helps in ensuring the product evenly heated. The product motion reduces the thickness of the boundary layer adjacent to the surface, speeds up the heating process and mixes the components of the product.

STEAM TRAPS

Steam trap is a device used for minimising the amount of air and condensate present in a jacket, when steam is used a heating medium.

Steam trap is attached to the apparatus (equipment), so that maximum heating efficiency is achieved. Generally at least two traps are installed to a jacketed vessel.

(a) One trap is attached at the bottom of the jacket for removing the condensate during the heating process.

(b) Second trap is attached at the top of the jacket on the opposite side to the steam entry. The air initially present in the jacket is flushed out (vent).

Reasons for using Steam Traps

Condensate has to be removed from the jacket for the following reasons.

- If the condensate is allowed to build up, it will gradually reduce the area over which steam can condense. Therefore, heating process is progressively slowed down.
- If the condensate completely fills the jacket, then heating stops.

Air has to be removed from the jacket for the following reason. If the steam is contaminated with air, the steam temperature decreases, less than the (water) boiling point at any operating pressure.

Simple drainage pipe connecting the jacket would be ineffective in removing the condensate and air, as it will not allow the steam to escape, which would be both wasteful and potentially dangerous. Condensate as well as air can be removed using a suitably designed steam trap, while retaining the steam in the jacket.

Types of Steam Traps

Float type mechanical steam trap : The construction of a floating type mechanical steam trap is shown in Figure 5-20. The principle of steam trap is as follows. The condensate settles at the bottom of the jacket, as it is denser than water. Then it enters into the trap. After sufficient accumulation, the condensate makes the ball (floating) to float. It results in raised position making the outlet to open and allowing the condensate to drain through the outlet.

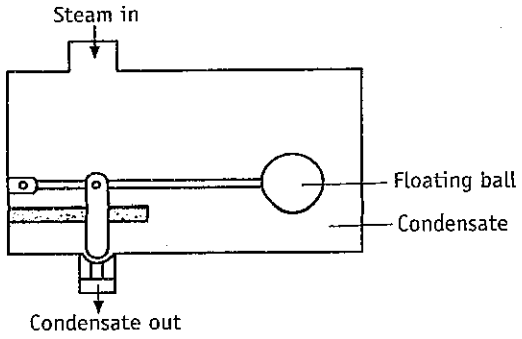


Figure 5-20. Float type mechanical steam trap.

Disadvantage : Float type mechanical steam trap does not allow air to escape, as the condensate is in contact with the trap outlet.

Bucket steam trap : The construction of a bucket steam trap is shown in Figure 5-21. It functions based on the weight of the bucket.

The bucket steam trap remains floating in its initial position. Once sufficient quantity of condensate is available inside, the bucket moves

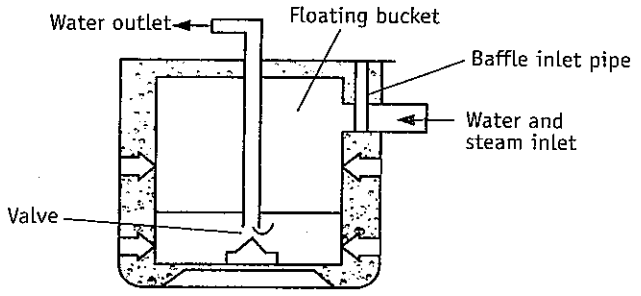


Figure 5-21. Bucket steam trap.

down making the value to open. Then the condensate is blown out through the outlet emptying the bucket. Again the bucket moves up reaching its floating position and then the valves closes. Thus, it is an intermittent discharge.

Balanced pressure thermostatic steam trap : Thermostatic devices work on the principle that condensate can lose sensible heat resulting in lower temperature than the steam. One example of this type is the 'balanced pressure thermostatic steam trap'.

The construction of a 'balanced pressure thermostatic steam trap' is shown in Figure 5-22. The trap is usually constructed using a material with good thermal conductivity, for example, copper. The opening and closing of this trap is based on the changes in temperature (or pressures). The trap contains a capsule in the form of bellows. It contains a liquid, which is having a boiling point a few degrees less than that of water. The mechanism of its functioning is shown in Figure 5-23.

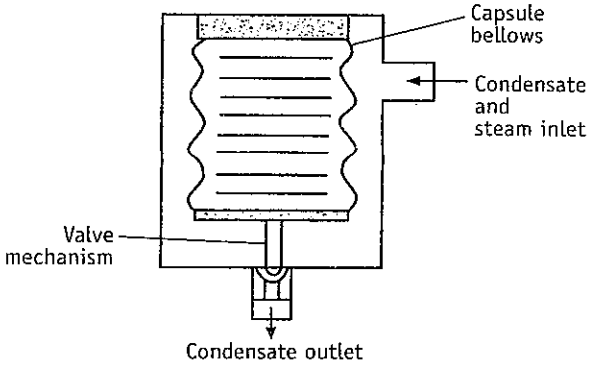


Figure 5-22. Balanced pressure thermostatic steam trap.

- *Closing of trap* : When the capsule is surrounded by steam, the liquid in the capsule boils causing the bellows to expand. Hence, the outlet is closed. Steam gets accumulated over a period of time and soon it gets condensed.

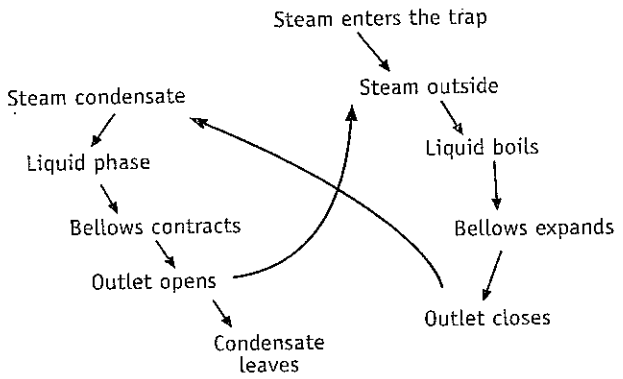


Figure 5-23. Mechanism of function of balanced pressure thermostatic steam trap.

- *Opening of trap* : When condensate enters the trap, it will lose sensible heat resulting in decreased temperature. The condensate cools the capsule and the liquid in the capsule ceases to boil. The bellows contract. Thus the outlet is opened. Condensate gets drained off.

As the temperature of the steam increases, the pressure also increases, which has an effect on the bellow and controls the valve. Hence, this trap is known as *balanced pressure steam trap*.

The condensate released from the trap also possesses significant amount of heat energy. It may be fed back to the steam boiler or used for other manufacturing plants or air conditioning systems.

Advantages : Air vent from the jacket is achieved. Otherwise air tends to collect at the bottom of the jacket.

Disadvantages : It is less robust than float type mechanical steam trap and bucket steam trap.

Entrainment

Entrainment is a term used to describe the loss of liquid frothing or 'blowing over' during evaporation.

In evaporation, the condensate is usually a pure solvent. In certain types of evaporators, the condensate also contains active principles of small proportion. E.g. liquid extract of cascara and liquiorice (coloured). This is possible, because particles of the liquid have been carried over mechanically with the vapour. During rapid boiling, the particles are aligned vertically in the solvent and carried away with the vapour.

When vacuum evaporation is employed, entrainment is very troublesome, because of the high velocity of the expanded vapour. In these systems, entrainment separators are designed to allow the free passage of vapour, but obstruct the passage of liquid particles.

Special separators are attached to the equipment, e.g. cyclone separator. In this, the vapour is introduced tangentially to its periphery, causing a circular motion of vapour. The centrifugal force caused the suspended droplets to be deposited. The separation of vapour from foaming liquid often presents difficulties. Loss of product may be serious in spite of the use of entrainment separators.

Foams and Prevention

Foam is possible, when the liquid is colloidal in nature or surfactants are present. For a liquid having a tendency to froth, complete separation of liquid particles appears to be impossible in vacuum evaporation. Along the foam, certain amount of liquid particles appears. Thus entrainment is inevitable. The objective is to keep this loss to a minimum. Antifoaming agents are often effective. Other means is to include steam jet impingement of foam.

Comment 5-10. What is the difference between steam trap and drainage pipe in handling steam?

Summary

Heat flow is a unit process and used in unit operations, such as evaporation, distillation, drying, crystallization and sterilization. The principles of thermodynamics are applied to explain the flow of heat that enters or leaves the system, whether the system undergoes a physical transformation or a chemical reaction. The flow of heat occurs from a hot fluid (steam, heat source) to a cold fluid (the place to interest). This process is achieved at an industry scale. Heat flows by different mechanisms: conduction (through metal shell of a boiler), convection (mixing of warmer portions and cooler portions as in boiling) and radiation (by means of electromagnetic waves, e.g. solar water heater). Though mechanisms are described separately, several of these operate simultaneously.

Heat can flow by conduction, when there is a temperature gradient across the metal shell. The direction of heat flow is from a hot surface to a cold surface. The heat flow depends on the conductivity of the material (metal). The conduction of heat through a metal wall is explained by Fourier's law. The rate of flow is directly proportional to area and temperature gradient and inversely proportional to the thickness of the meal wall. The greater the temperature gradient, the greater will be the rate of heat flow. The outcome of the Fourier's law is the coefficient of resistance (proportionality constant) or coefficient of thermal conductivity. Metals have high coefficients of thermal conductivity. These principles are applied in the construction of evaporators and tubular heat exchangers, i.e. metal having high thermal coefficient is considered, normally copper. The same law is also extended to obtain compound-resistance in series, heat flow through

cylindrical pipes. Conduction also occurs in fluids, except when heat flows through the thin films.

Heat flow by convection is achieved by actual mixing layers of liquids. Convection fluid flow and their nature (laminar or turbulent) decide the behavior of heat flow. This type of transfer may be forced convection (as in forced evaporators) or natural convection (as in pan evaporator). In forced convection, a stirrer or agitator or pumping is used for recirculation. The heat transfer in a tube, heat must pass through the stagnant film by conduction. Normally, thermal conductivities of fluids are low. In a forced convection type, heat transfer process is evaluated considering the stagnant film coefficients and overall heat transfer coefficients. Natural convection is observed when extracts are evaporated in pans. In natural convection, the hot liquid (steam) gives the heat, while the cold liquid receives heat (boiling). The film coefficients decrease with increasing the temperature drop. If steam is the heating medium, the steam condenses on the surface of the metal tube drop-wise and ultimately may form continuous firm. The coefficients for drop-wise condensation are double or more than double that of the film coefficients. In hot fluid-to-cold fluid type, the maximum heat flux is observed at higher temperature differences. When hot fluid-to-cold fluid system, heat transfer may be achieved depending on the mode of introducing the feed: parallel or counter-current to the flow of cold fluid. In parallel mode, the overall heat transfer coefficient (U) is related to the logarithmic mean temperature difference. In the counter-current, the overall heat transfer coefficient is related to the average temperature difference. These principles help in design the process of heat transfer.

Radiation is an energy transfer process in which heat is transferred through space by means of electromagnetic waves. Thermal radiation usually occurs simultaneously with heat transfer by convection and conduction. The rate of radiation is explained by Stefan-Boltzmann law and the amount radiation emitted by a black body is quantified. The thermal energy by radiation increases rapidly with temperature. A black body absorbs all the radiation falling on it. At the same time, it radiates maximum possible amount of energy at a given temperature. A grey body is defined as that body whose absorptivity is constant at all wavelengths of radiation at a given temperature.

Most of the chemical and pharmaceutical industries employ a variety of heat transfer equipment. In the working, the heating medium is not fluid (condensed steam) and other side, material is present (liquid, gases or solids). Based on the working, two types of equipment are referred: heat exchanger and heat interchangers. Heater or heat exchangers are: tubular heater, multipass heater and floating-head heater. In these, the heat transfer becomes less. Hence efficiency is improved by passing the liquid at a high

velocity. These are useful, because of high values of steam film coefficients. Heat interchangers are: liquid-to-liquid interchanger and double pipe heat interchanger and scraped film heater. In heat interchangers, the heat transfer is from a hot liquid to a cold liquid or a hot gas-to-cold gas through metal wall. The heat transfer is not efficient, but velocity can be increased, which is difficult. Hence, surface area of contact is increased. Baffles are placed on the tubes.

Steam is water in the vapour state. Steam has a high latent heat of condensation per unit weight. Therefore, steam is an effective heating medium on industrial scale. It is economical and cheaper than that of electricity. Normally saturated steam is used for heating the equipment. Steam is produced in a steam boiler at high pressure, which becomes the driving force for the distribution of steam. High pressure increases the temperature and also the sensible heat. The low pressure exhaust steam is used for process heating. Process vessels are made of stainless steel with an acceptable thermal conductivity. The outer surface of the jacket is made with material having poor thermal conductivity. Steam is delivered to the process vessel through lagged pipes to the steam inlet. The steam after entering the jacket condenses and releases the latent heat for transfer. After condensing, the steam contracts to a small volume and creates an area of low pressure within the jacket into which more steam will then flow. Steam traps are fitted to the process vessel, so that condensate is removed at the bottom and air is removed from the top of the jacket. Entrainment separators are included to obstruct the passage of liquid particles. Froth, if any, is removed by adding antifoaming agents. Thus the heat flow becomes effective to the equipment.

Glossary of Symbols

A = Area of the heating surface, m^2.
A_m = Mean area of a cylinder, m^2.
b = Stefan Boltzmann's constant, $W/m^2 \cdot K^4$.
h = Sensible heat, kJ.
h_1 = Surface coefficient on the hot side, $W/m^2 \cdot K$.
h_2 = Surface coefficient on the cold side, $W/m^2 \cdot K$.
k_m = Mean proportionality constant, $W/m \cdot K$.
L = Thickness of the heating surface, m.
L = Latent heat of vapourization, J/kg.
m = Mass of water, kg.
N = Length of the hollow cylinder, m.
q = Rate of heat transfer, W (J/s).
q = Dryness fraction of wet steam.
Q = Latent heat of steam, J/kg.

r = Radius of the thin cylinder for heat transfer, m.
r_m = Logarithmic mean radius, m.
s = Specific heat capacity, kJ/kg.K.
T = Absolute temperature, K.
t_1 = Temperature at the hot surface, K.
t_2 = Temperature at the cold surface, K.
ΔT = Temperature rise, K.
Δt_m = Arithmetic average temperature difference, K.
Δt = Temperature difference, K.
U_1 = Overall heat transfer coefficient on hot side, $W/m^2 \cdot K$.
U_2 = Overall heat transfer coefficient on cold side, $W/m^2 \cdot K$.
α = Absorptivity.
ρ = Reflectivity.
τ = Transmissivity.
ε = Emissivity.

QUESTION BANK

Each question carries one mark

Note : Encircle the alphabet which corresponds to the single best response.

1. In the heat interchanger, finned tubes are used for one of the following purposes.
   A. Increasing the surface area
   B. Introducing steam
   C. Introducing the cold fluid
   D. Reducing the size of apparatus
2. The general equation for heat transfer rate, q, is expressed as:
   A. $A\Delta t/U$
   B. $U/A\Delta t$
   C. $UA\Delta t$
   D. $UA/\Delta t$
3. For heat insulation, one of the following is used.
   A. Aluminum wire
   B. Copper foils
   C. Glass wool
   D. Iron fehlings
4. In double pipe heat exchanger, the two tubes are arranged in one of the following ways.
   A. Coaxial
   B. Concentric
   C. Parallel
   D. Series
5. Which heat interchanger consists of bent tubes?
   A. Double pipe heat exchanger
   B. Floating head two pass heater
   C. Multi pass heater
   D. Tubular heater
6. Fourier's law is applicable to one of the following types of heat flow.
   A. Conduction
   B. Convection
   C. Emission
   D. Radiation

7. Flow of heat is NOT applicable generally in one of the following unit operations.
   A. Centrifugation
   B Crystallization
   C. Drying
   D. Refrigeration
8. In microwave oven, the heat flows in one of the following mechanisms.
   A. Conduction
   B. Convection
   C. Diffusion
   D. Radiation
9. In convection process for a liquid in a tube, one of the following offers great resistance.
   A. Central layer of liquid
   B. Liquid layer adhered to the metal wall
   C. Metal wall
   D. Stagnant liquid layer between viscous and turbulent flow
10. In forced convection, the rate of heat transfer is increased by metal with:
    A. high thermal conductivity
    B. Metal with high thermal conductivity and mixing of fluid
    C. high thermal conductivity, mixing of fluid and low viscous fluid
    D. high thermal conductivity, mixing of fluid, high viscous fluid and more area of heating surface
11. Which one of the following bodies radiates maximum amount of energy at a given temperature?
    A. Black body
    B. Grey body
    C. Light grey body
    D. Polished black body
12. Heat exchangers are NOT used in one of the following unit operations.
    A. Crystallisation
    B. Drying
    C. Evaporation
    D. Size separation
13. Which heater is a highly efficient heat interchanger?
    A. Double pipe heater
    B. Multi pass heater
    C. Tubular heater
    D. Two pass floating head heater
14. Loosening of tube sheets is a serious disadvantage in many heat exchangers EXCEPT:
    A. Double pipe heater
    B. Floating head heater
    C. Multi pass heater
    D. Tubular heater
15. What is the purpose of baffles in a heat exchanger?
    A. Allowing a single pass
    B. Increasing the cross-section of path
    C. Increasing the path of travel
    D. Reducing turbulence

16. Which medium is the most effective for thermal radiation?
    A. Air
    B. Insulated with cotton
    C. Vacuum
    D. Water
17. A black body satisfies one of the following conditions.
    A. Absorbs less energy than it receives
    B. Absorbs energy, it receives
    C. Radiates all the energy it receives
    D. Radiates less energy than it receives
18. In the calculation of heat transfer by convection through parallel flow feed, one of the following is used to represent the variation in temperature.
    A. Arithmetic mean
    B. Geometric mean
    C. Logarithmic mean
    D. Log-logarithmic mean
19. Which type of steam is NOT suitable for heat transfer?
    A. Dry steam
    B. Steam at saturated temperature
    C. Steam at low pressure
    D. Super heated steam
20. Which type of mean radius is used in the calculation of heat flow, when heat flows through a thin walled circular pipe?
    A. Arithmetic
    B. Geometric
    C. Harmonic
    D. Logarithmic
21. Which one of the following has high thermal conductivity?
    A. Copper
    B. Glass
    C. Stainless steel
    D. Steel
22. Drop-wise condensation of steam is possible in one of the following conditions of pipes.
    A. Clean surface
    B. Greasy surface
    C. Rough surface
    D. Smooth surface
23. The surface film coefficient decreases by reducing the film thickness, which is achieved by:
    A. decreasing the turbulence
    B. increasing fluid flow
    C. increasing the mass of flow
    D. increasing the viscosity
24. Forced convection is applied in one of the following operations.
    A. Centrifugation
    B. Crystallisation
    C. Distillation
    D. Evaporation
25. According to Fourier's law, conduction of heat through a metal wall is:
    A. Inversely proportional to temperature difference
    B. proportional to area of metal wall
    C. proportional to thickness of wall
    D. proportional to weight of metal wall

26. Thermal conductivity and resistance of metals are related in the following proportionality.
    A. Direct
    B. Exponential
    C. Inverse
    D. Logarithmical
27. Which of the following is correct according to Stefan-Boltzmann law?
    A. $q = bAT$
    B. $q = bAT^2$
    C. $q = bAT^3$
    D. $q = bAT^4$
28. Which one of the following statements is NOT true with respect to fins in a heat transfer equipment?
    A. Fins enhance the rate of heat transfer
    B. Fins increase the surface area of contact
    C. Fins reduce the efficiency of heat exchanger
    D. Fins reduce the size of the apparatus
29. Which one of the following types of steam is used as a heating medium?
    A. Exhaust steam
    B. Saturated steam
    C. Superheated steam
    D. Wet steam
30. Which one of the following mechanisms is involved in the bucket type of steam trap?
    A. Electric current connectivity
    B. Mechanical force
    C. Temperature differences
    D. Weight basis
31. Which one of the following equipment is an example of heat transfer by radiation?
    A. Hot air oven
    B. Incubator
    C. Microwave Oven
    D. Refrigerator
32. Hot air is circulated (through a fan) in the hot air oven. What are the mechanisms operating in this heat transfer process?
    A. Conduction and forced convection
    B. Conduction and natural convection
    C. Conduction, forced convection and radiation
    D. Forced convection and radiation
33. What is NOT the driving force for the heat transfer in a circular pipe?
    A. Length
    B. Surface area
    C. Temperature difference
    D. Thickness
34. Heat transfer from a metal wall does NOT involve one of the following mechanisms.
    A. Conduction
    B. Convection
    C. Emission
    D. Radiation
35. Which one of the following is equivalent (in SI units - pressure, kPa) to one atmosphere?
    A. 1
    B. 100
    C. 101
    D. 1001

36. Which one of the following is responsible for the heat transfer by natural convection?
    A. Agitation
    B. Density of vapour
    C. Material of construction
    D. Surface area
37. What are the heat transfer mechanisms involved when the liquid is at low temperature and at high temperatures?
    A. Convection and conduction
    B. Convection and radiation
    C. Radiation and conduction
    D. Radiation and convection
38. The efficiency of a heat exchanger can be improved by passing the cold liquid at a high velocity. How does it improve?
    A. Thick film and high resistance
    B. Thick film and less resistance
    C. Thin film and high resistance
    D. Thin film and less resistance
39. The disadvantage of multipass heater is:
    A. friction losses are high
    B. heat transfer rate is low
    C. steam cannot be used
    D. velocity of the fluid flowing is low
40. The reason for arranging baffles in a liquid-to-liquid interchanger is NOT true.
    A. Increase the velocity of flow of outside liquid
    B. Enhance multipass of cold fluid
    C. Enhance the surface area of contact
    D. Create more turbulence

Each question carries 2 marks

1. Describe the types of condensation for saturated vapour free from non-condensible gases.
2. Give characteristics of drop-wise and film types condensation.
3. Drop-wise or film type condensation gives superior value of overall heat transfer coefficient and why?
4. List the characteristics of heat transfer by radiation.
5. What are 'Grey bodies'? How do they radiate heat?
6. Give the final equation for heat transfer by conduction through resistances in series and explain the terms.
7. What are 'overall heat transfer coefficient' and 'individual film coefficient'?
8. Explain the terms 'Black body' and 'Grey body'.
9. State the relationship between individual film coefficients and overall heat transfer coefficient.

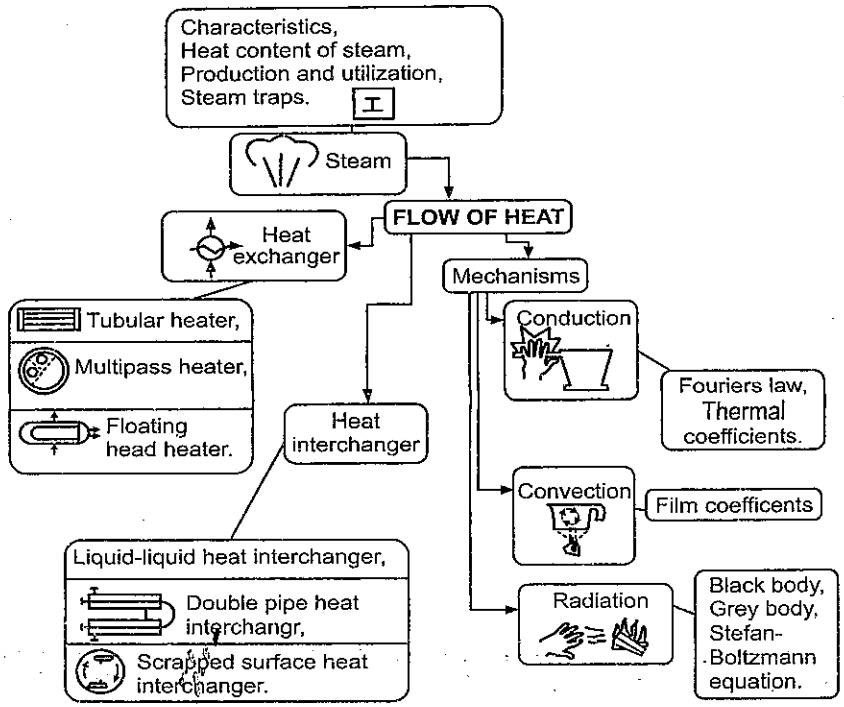
10. Define conductivity with a suitable example
11. State and explain Stefan Boltzmann's law of heat radiation.
12. State and explain Fourier's law of heat transmission with equation.
13. Explain 'nucleate boiling' and 'film boiling'.
14. Define radiation. Explain Stefan Boltzmann's law.
15. Write the final equation for heat transfer by conduction through resistances in parallel and explain the terms.
16. What is meant by overall heat transfer coefficient? What is its significance?
17. Differentiate between a heat interchanger and heat exchanger.
18. Write the differences between steam trap and drainage pipe in handling steam effectively.
19. Describe the term 'entrainment'. How is it prevented?
20. Describe the possible reasons for foaming.
21. Describe the advantages and disadvantages of steam boiler.
22. List four characteristics of steam.
23. List the advantages and disadvantages of two each of super heated steam.
24. Explain the terms 'dry saturated steam' and 'superheated steam'.
25. Explain the role of stagnant film in the flow of heat in liquids.

Each question carries 5 marks

1. Compare and contrast heat transmission following counter-current and parallel-current feed techniques with relevant equations.
2. Derive an equation for heat transfer by conduction through compound resistances in series.
3. Draw a neat and labelled diagram of a shell-and-tube heat exchanger and explain its construction.
4. Describe finned tube heat exchanger and its specific advantages.
5. Describe the conduction of heat through a circular pipe. Give suitable equations for rate of heat transfer and explain terms.
6. Describe the conduction of heat through compound resistances in series.
7. Derive an expression for determining the logarithmic mean temperature difference.
8. Describe liquid heat interchangers. What are its advantages?
9. Explain the working of any one heat exchanger with a labelled diagram.
10. Explain the construction and working of 'balanced pressure steam trap.
11. Describe the construction of a pharmaceutical process vessel with different steam controls.
12. Explain the term 'steam trap' giving a suitable example.
13. Describe steam as an ideal heating medium.

Each question carries 10 marks

1. With the help of a neat diagram, explain the concept of film and overall heat transfer coefficients in forced convection. Deduce relevant mathematical equations.
2. Derive an equation for heat transmission through a circular pipe from Fourier's law.
3. Describe the construction, operation, advantages and disadvantages of a multipass heater.



MIND MAP OF HEAT FLOW

CHAPTER 6

Evaporation

Factors Influencing Evaporation
Classification of Evaporators
Equipment
Theory
Multiple Effect Evaporator

LEARNING OBJECTIVES

After reading this chapter, the reader should be able to:

- Appreciate the principles of evaporation with applications.
- Understand the theory describing evaporation with a view to evaluate the capacity and efficiency.
- Explain the designs of different industrial evaporators along with working and uses.
- Select a suitable evaporator based on the properties of the materials.

Evaporation is a process of vaporising large quantities of volatile liquid to get a concentrated product.

Equipment used for the evaporation are known as *evaporators*. Heat is supplied to the evaporator, which transmits it to the evaporating liquid so as to provide latent heat of vaporisation. Steam is normally used as a source of heat. Evaporation is a surface phenomenon, i.e. mass transfer takes place from the surface. Thus no boiling occurs. In practice, surface evaporation is slow. Therefore, *the practical definition of evaporation* is the removal of solvent from the solution by boiling the liquor in a suitable vessel and withdrawing the vapour, leaving a concentrated liquid residue in the vessel.

Either solutions or suspensions can be subjected to evaporation. The only condition is that the liquid must be volatile, while the solute must be nonvolatile. Since heat is supplied, the constituents should be thermostable. In most of the operations, the liquid is water with a low solid content. The liquid to be evaporated may be less viscous than water or it may

be so viscous that it will hardly flow. At the end of the process, the concentrate will be so viscous that further evaporation will be drastically reduced.

Evaporation some times overlap with other heat processes, though some distinctions can be drawn. These are given in Table 6-1. Although the purpose of evaporation is to obtain a concentrated product, the solvent vapour is sometimes valuable, so recovery is essential. This prevents the environmental pollution, fire hazards and at the same time makes the process economical.

TABLE 6-1

Distinguishing Features of Evaporation with other Heat Processes

S. No.	*Evaporation*	*Other heat process*
1	The residue is a concentrated liquid.	*Drying* : the residue is solid.
2	Evaporating liquid is only one component in most of the cases.	*Distillation* : Evaporating liquid is a combination of two or more components.
3	No attempt is made to separate the mixture of vapour, even if any.	*Distillation* : It is compulsory to separate each component.
4	The purpose of evaporation is to get a concentrated liquid only, but not to get crystals as it happens in some situations.	*Crystallization* : The purpose of concentrating the solution is to get crystals.

Applications

Manufacture of bulk drugs : Evaporation process is used in pharmacy practice, pharmaceutical industries, chemical industries, etc.

Manufacture of biological products : Evaporation is used in the manufacture of biological products such as insulin, biochemical products (example is penicillin) and plant products. Preparation of blood products such as blood plasma and serum involves evaporation. Enzymes, hormones and antibiotics are prepared.

Miscellaneous : Water containing minerals is subjected to evaporation to get demineralised water after condensation. The water so obtained is used for human consumption and for special processes. This is some sort of evaporation though the process is generally called distillation.

Comment 6-1. Is the evaporation a surface phenomenon or bulk phenomenon? Explain.

Comment 6-2. The objective of the evaporation is to obtain crystals. True or false. Explain.

Comment 6-3. What way is drying be different from evaporation?

Comment 6-4. Evaporation and distillation are similar. True or false. Explain.

FACTORS INFLUENCING EVAPORATION

The rate of evaporation depends on several factors. The relationship may be expressed mathematically as:

$$M = \frac{KS}{p}(b - b') \qquad ...(1)$$

where M = mass of vapour formed per unit time (Rate), m^3/s
S = surface area of the liquid exposed, m^2
p = atmospheric pressure, kPa
b = maximum vapour pressure at the temperature of air, kPa
b' = pressure due to the vapour of the liquid, actually present in the air, kPa
K = constant, m/s

In general mass transfer also depends on the temperature.

Temperature

The higher the temperature, the greater the value of b and hence greater will be the evaporation.

At a given temperature, some molecules possess higher kinetic energy than average, while others have lower than average kinetic energy. Fast moving molecules escape from the surface of the liquid into vapour, while slow moving ones remain behind. When temperature of the liquid is raised, more molecules acquire sufficient kinetic energy and escape from the surface to vapour state. This is the situation below the boiling point of the liquid.

Below boiling point, vapour is formed from the surface only. At boiling point, vapour is formed throughout the body of the liquid as well as from surface. The vapour pressure of a liquid is lowered when a substance is dissolved in it and consequently the boiling point of the liquid increases.

Normally, glycosides and alkaloids decompose at high temperature. Hormones, enzymes and antibiotics are even more heat-sensitive. These products require special techniques to prevent decomposition during evaporation. For example, malt extract is prepared by evaporation under reduced pressure to avoid loss of enzymes. Antibiotics are concentrated by freeze-drying.

Vapour Pressure

Rate of evaporation is directly proportional to the vapour pressure of the liquid. The lower the p value in equation (1), the greater the evaporation. Lower the external pressure, the lower the boiling point of the liquid and hence greater will be the rate of evaporation. This condition is achieved by applying vacuum.

The nature of liquid is also important for rate of evaporation. Liquids with low boiling points evaporate quickly because of high vapour pressures at lower temperatures.

If the outer atmosphere is dry, the value of b' will be low and hence greater the evaporation. If the vapour of the liquid is removed as soon as it is formed (under reduced pressure or vacuum), the space above the liquid does not become saturated with the vapour. Hence, evaporation proceeds faster.

Surface Area

From equation (1), it is clear that the greater the surface area of the liquid, the greater will be the evaporation. For this reason, evaporation is conducted in evaporators with larger heating surface area.

Moisture Content of the Feed

Some drug constituents undergo hydrolysis readily in presence of moisture at high temperatures. To prevent decomposition, the material is exposed to lower temperature initially, then exposed to higher temperature for final concentration. For example, dry extract of belladonna is prepared in this manner.

Type of Product Required

Type of product required some times decides the apparatus for evaporation. Open pan produces liquid or dry concentrate. Film evaporator yields liquid concentrate. Spray dryer produces dry products with good solubility. Vacuum evaporator gives porous product suitable for conversion to granules, for example, preparation of granular extract of cascara for tablet making.

Time of Evaporation

If the time of exposure is longer, greater will be the evaporation, provided the constituents are thermostable. Exposure of a drug to a relatively high temperature for a short period of time may be less destructive of active principles than a lower temperature with long exposure period. For this reason, film evaporators are used.

Film and Deposits

When vegetable extracts are concentrated in steam pan, a film may be formed on the surface and/or precipitated matter may deposit on the heating surface. Film reduces the evaporating surface and precipitated matter hinders the transfer of heat. To avoid these problems, efficient stirring is necessary.

Economic Factors

Economies of labour, fuel, floor space and materials are of primary considerations. The recovery of solvents and the utilization of *waste heat* are also important as they involve considerable reduction of costs.

For evaporation, heat is necessary to provide the latent heat of vaporisation. Hence, rate of evaporation is controlled by rate of heat transfer. Therefore, evaporator is designed to give maximum heat transfer to the liquid.

CLASSIFICATION OF EVAPORATORS

I. Evaporators with heating medium in jacket
   Example: Steam jacketed kettle (evaporating pan)
II. Vapour heated evaporators with tubular heating surfaces
   (A) Evaporators with tubes placed horizontally
      Examples : Horizontal tube evaporator
   (B) Evaporators with tubes placed vertically
      (i) Evaporators with short tubes
         (a) Single effect evaporators
            Examples : Short tube vertical evaporator (Standard vertical tube evaporator)
               Short tube vertical evaporator with propeller
               Basket type evaporator
         (b) Multiple effect evaporator
            Example : Triple effect evaporator
      (ii) Evaporators with long tubes
         (a) Evaporators with natural circulation
            Examples : Climbing film evaporator (Rising film evaporator)
               Falling film evaporator
         (b) Evaporators with forced circulation
            Example : Forced circulation evaporator

Critical Quality Attributes – Evaporation

The critical quality attributes (CQAs) along with process parameters (PPs) for evaporation are recorded in Figure 6-1. Evaporation involves concentrating the feed and is considered in the context of obtaining fluid extracts or API crystals. The upstream process (before evaporation) is either distillation or extraction and downstream operation is drying or

packing the product for the storage or crystallization. The critical quality attributes are: the nature of residue (chemical: liquid/solid, assay/purity) and flow properties.

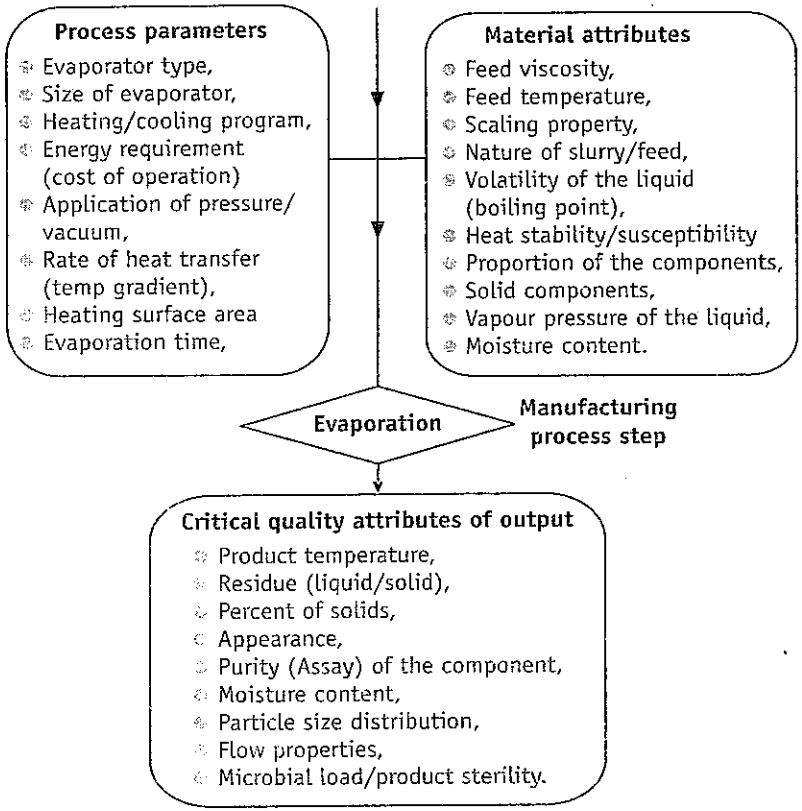


Figure 6-1. Process parameters and critical quality attributes for evaporation for obtaining solid residue.

The process parameters optimized are: rate of heat transfer and consequent mass transfer rate, though both decide the time of evaporation. Suitable devices are applied to make the process efficient. The material attributes primarily are the volatility or partial vapour pressure of the solvent.

EQUIPMENT

Steam Jacketed Kettle or Evaporating Pan

Principle : Steam is supplied to a jacketed kettle (evaporating pan) in which aqueous extract is placed. Steam gives out heat to the kettle. The heat is transferred to the aqueous extract by conduction and convection. The temperature raises and the escaping tendency of the solvent molecules

into vapour increases. Stirring further enhances the vaporisation of solvent molecules.

Construction : The construction of a steam jacketed kettle is shown in Figure 6-2. It is a hemispherical structure consisting of an inner pan called *kettle*. It is enveloped with an outer pan called *jacket*. The two pans are joined to enclose a space through which steam is passed.

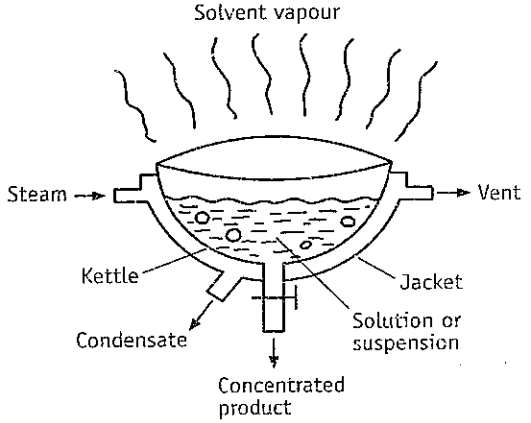


Figure 6-2. Steam jacketed kettle.

For smaller quantities, kettle is made up of a single sheet of metal. For larger capacities, several sheets are welded. Though several metals are used as a material of construction, for practical purposes the following are used. Copper is an excellent material for the kettle, because of its good conductivity. If acidic materials are evaporated, some quantity of copper would dissolve. For such preparations, tinned copper is used. Iron is used for the construction of the jacket, because it has minimum conductivity. To prevent rusting of the jacket, the iron is either tinned or enamelled on inner surface.

An inlet for the steam and an outlet (vent) for noncondensed gases are provided near the top of the jacket. Condensate leaves the jacket through the outlet provided at the bottom. The kettle is provided with one outlet for product discharge at its bottom.

Working : Aqueous extract to be evaporated is placed in the kettle. Steam is supplied through the inlet. Steam gives out its heat to the contents and the condensate leaves through the outlet. The contents must be stirred manually for smaller volumes and mechanically for larger volumes. Mechanical stirrer is not shown in Figure 6-2. The rate of evaporation is fast in the initial stages and decreases gradually as the liquid gets concentrated.

Any room where evaporation is carried by this apparatus must have good ventilation to remove the vapour. Otherwise, the room is quickly

filled with a dense fog of condensed vapour and water falls from the roof and runs down the walls. Fans fitted over the pan not only remove the vapour and prevent condensation in the room, but also accelerate the rate of evaporation by quickly removing saturated air from the surface of the liquid.

The kettle may be fixed or made to tilt. A kettle of capacity upto about 90 L may be made to tilt. But above this capacity, the weight of the pan along with its contents becomes too great to tilt. Hence, the bottom outlet is used to collect the concentrated product.

Uses : Evaporating pan is suitable for concentrating aqueous and thermostable liquors, e.g. liquorice extract.

Advantages : (1) Evaporating pan is constructed both for small scale and large scale operations.

(2) It is simple in construction and easy to operate, clean and maintain.

(3) Its cost of installation and maintenance is low.

(4) Wide variety of materials can be used for construction such as copper, stainless steel and aluminium.

(5) Stirring of the contents and removal of the product is easy.

Disadvantages : (1) In evaporating pans, heat economy is less. Hence, cost per unit material production is more.

(2) It is not suitable for heat sensitive materials due to long time of exposure.

(3) The heating area decreases as the product gets more concentrated.

(4) As it is open type, vapour passes into the atmosphere, which can lead to saturation of the atmosphere, slowing evaporation as well as causing discomfort.

(5) Boiling point of water cannot be reduced, since reduced pressure cannot be created in open type evaporator.

Horizontal Tube Evaporator

Principle : In horizontal tube evaporator, steam is passed through the horizontal tubes, which are immersed in a pool of liquid to be evaporated. Heat transfer takes place through the tubes and the liquid outside the tubes gets heated. The solvent evaporates and escapes from the top of the evaporator. The concentrated liquid is collected from the bottom.

Construction : The construction of a horizontal tube evaporator is shown in Figure 6-3. It consists of a large cylindrical body with conical or dome-shaped top and bottom. It is made up of cast iron or plate steel. An

average size of the body ranges from 1.8 to 2.4 m diameter and from 2.4 to 3.6 m height.

The lower part of the body consists of a steam compartment with an inlet for steam at one end and a vent for noncondensed gases on the other end. A condensate outlet is provided at the bottom of the steam compartment. In the steam compartment, 6-8 stainless steel horizontal tubes are placed. The tubes are cut long enough so that they project about 25.0 mm beyond the tube sheet on both ends. The width of steam compartment is usually half the diameter of the body.

At one convenient point, an inlet for feed is provided (Figure 6-3). One outlet for vapour is placed at the top of the dome. Another outlet for thick liquid is placed at the centre of the conical bottom of the body.

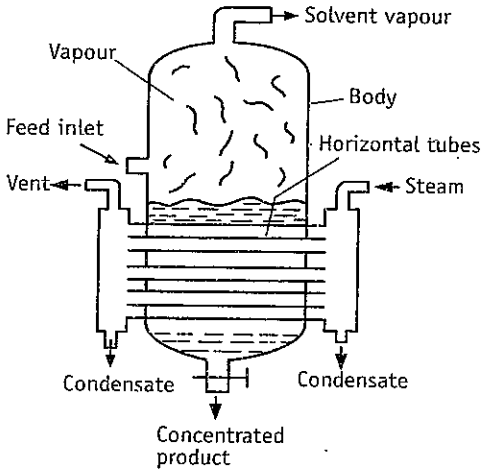


Figure 6-3. Construction of a horizontal tube evaporator.

Working : The feed is introduced into the evaporator until the steam compartment is satisfactorily immersed. Steam is introduced into the steam compartment. The horizontal tubes receive heat from the steam and conduct it to the liquid due to temperature gradient. Steam condensate passes through the corresponding outlet. The feed absorbs heat and solvent gets evaporated. The vapour then escapes through the outlet placed at the top. This process is continued until a thick liquid is formed, which can be collected from the bottom outlet.

Uses : Horizontal tube evaporator is the best suited for non-viscous solutions that do not deposit scales or crystals on evaporation, e.g. cascara extract.

Advantage : The cost per square metre of heating surface is usually less in horizontal tube evaporator.

Vertical Tube Evaporator (Short Tube Evaporator)

Principle : In standard vertical tube evaporator, liquid is passed through the vertical tubes and the steam is supplied from outside the tubes. Heat transfer takes place through the tubes and the liquid inside the tubes gets heated. The solvent evaporates and the vapour escapes from the top. The concentrated liquid is collected from the bottom.

Construction : The construction of a standard vertical tube evaporator is shown in Figure 6-4. It consists of a large cylindrical body made up of cast iron with dome shaped top and bottom (Figure 6-4). In side the body, calandria is fitted at the bottom. Calandria consists of a number of vertical tubes, whose diameter ranges from 0.05 to 0.075 m and length of 1-2 m. About 100 such tubes are fitted in a body measuring 2.5 m or more diameter. Inlets are provided for steam and feed. Outlets are provided for vapour, concentrated product, non-condensed gases and condensate.

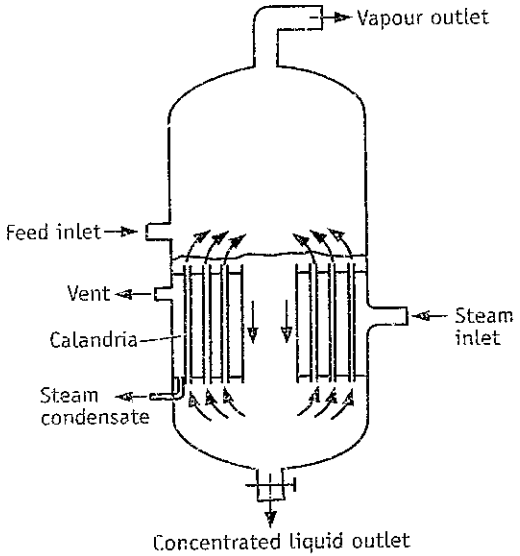


Figure 6-4. Construction of a short tube evaporator.

Working : Steam is introduced outside the tubes. The condensate is passed through the corresponding outlet and non-condensed gases escape through the vent. The feed is introduced in such a way as to maintain the liquid level slightly above the top of the tubes. The liquid inside the tubes is heated by the steam and begins to boil. As the liquid boils, it spouts up through the tubes and returns through the central down-take. It sets up a circulation of hot liquid, which enhances the rate of heat transfer. The vapour escapes through the top outlet. Steam is supplied until required

concentration of the product is obtained. Finally, the product can be withdrawn from the bottom outlet.

Uses : Vertical tube evaporator is used in the manufacture of Cascara extract, sugar, salt and caustic soda.

Advantages : (1) In vertical tube evaporator, tubes increase the heating surface nearly 10 to 15 times when compared with steam jacketed kettle.

(2) Vigorous circulation enhances the rate of heat transfer.

(3) It can be connected to a condenser and receiver, which further increases rate of evaporation. Such attachment is also suitable for volatile solvents.

(4) A number of units can be joined to obtain more efficient effect (multiple effect evaporators which work for this effect are discussed later).

Disadvantages : The liquid is maintained above the level of the calandria. Hence, the upper layers of the liquid need a long time for getting heated. This problem can be minimised by removing concentrated liquid slowly at the bottom.

The evaporator is complicated, hence, installation cost increases.

Cleaning and maintenance is difficult when compared with steam jacketed kettle.

During operation, the pressure inside the evaporator increases. In large evaporators, where the liquid depth may be of the order of 2.0 metres, the pressure increases to 25.0 kilopascals, leading to elevation of the boiling point by 5 or 6 °C. This reduces the effective temperature gradient and may affect heat sensitive materials.

Variants : *Short tube vertical evaporator with propeller* : In short tube vertical evaporator, circulation depends completely on boiling. Steam is supplied into the calandria to induce boiling. When steam supply is stopped, automatically boiling stops. As a result the particles (if any) settle down. These particles act as nuclei which grow as crystals. Therefore, this evaporator is sometimes used as a crystallizing evaporator. If such crystallization is undesirable, the problem can be avoided by installing a propeller in the central portion close to the bottom. By increasing the revolutions per minute of the propeller, the capacity of the evaporator can be doubled.

Uses : Since mild steel or cast iron is used, the evaporator suits well for clear liquids and crystallizing solutions. Non corrosive liquids and mild scaling solutions can also be handled.

Advantages : Heat transfer coefficients are high due to high temperature gradient values. It requires low head-room. Cleaning and maintenance is easy. It is relatively inexpensive.

Disadvantages : Heat transfer is poor at low Δt values. It requires high floor space and is more in weight. Relatively more liquid is retained. Rate of heat transfer further decreases due to high viscosity liquids. Since body is large, mild steel or cast iron are used for its construction to make it less expensive.

Basket type evaporator : The basket type of evaporator has a conical bottom and some times a flat bottom. In this type, boiling is quite violent. Hence, the spouting of the liquid leads to entrainment. This problem can be avoided by placing a deflector over the tubes. In this case, the down-take is annular instead of being central. The advantage of this type is that entire heating element is a single unit. The complete unit can be removed for repairs. In addition, the deflector prevents entrainment losses completely.

Climbing Film Evaporator (Rising Film Evaporator)

Principle : In climbing film evaporator, tubes are heated externally by steam. The preheated feed enters from the bottom and flows up through the heated tubes. The liquid gets heated rapidly due to enhanced overall coefficient of the preheated feed. The liquid near the wall becomes vapour and forms small bubbles. These tend to fuse to larger bubbles, which travel up in the tubes along with entrapped slug. The liquid films are blown up from the top of the tubes and strikes entrainment separator (deflector) kept above. This throws the liquid concentrate down into the lower part from where it is withdrawn.

Construction : The construction of a climbing film evaporator is shown in Figure 6-5. In this evaporator, the heating unit consists of steam jacketed tubes. Here, the tubes (long and narrow) are held between two plates. An entrainment separator is placed at the top to the vapour head. The evaporator carries steam inlet, vent outlet and condensate outlet. The feed inlet is from the bottom of the steam compartment.

Working : The preheated liquid feed (to be evaporated) is introduced from the bottom of the unit. The height of the liquid column is maintained low, i.e. 0.6 or 1.2 m above the bottom tube sheet. Steam enters into the spaces outside the tubes through the inlet. Heat is transferred to the liquor through the walls of the tubes. The liquid becomes vapour and forms smaller bubbles, which tend to fuse to larger bubbles. These are of the width of the tubes, thereby the bubbles trap a part of the liquid (slug) on its way up in the tubes facilitating the liquid to spread as a film over the walls. This film of liquid continues to vaporise rapidly. Finally, the mixture of liquid concentrate and vapour eject at a high velocity from the top of the tubes.

The entrainment separator not only prevents entrainment, but also acts as a foam breaker. The vapour leaves from the top, while concentrate is collected from the bottom.

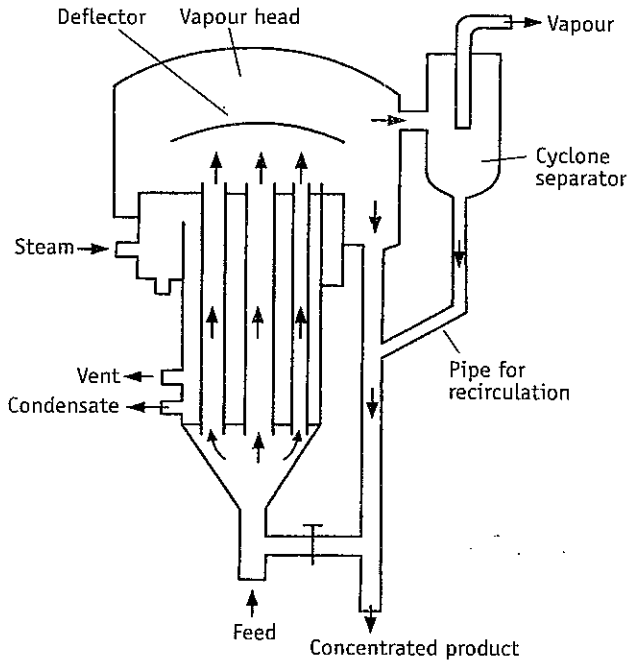


Figure 6-5. Construction of a climbing film evaporator.

Uses : Using climbing film evaporator, thermolabile substances such as insulin, liver extracts and vitamins can be concentrated. Clear liquids, foaming liquids and corrosive solutions in large quantities can be operated. Deposit of scales can be removed quickly by increasing the feed rate or reducing the steam rate so that the product is unsaturated for a short time.

Advantages : (1) In a climbing film evaporator, large area for heat transfer is provided employing long and narrow tubes.

(2) Since liquid flows at a high velocity, the resistance for heat transfer at the boundary layers is reduced. As a result, the heat transfer is enhanced.

(3) The time of contact between the liquor and the heating surface is very short. The liquid is in the heater for one second, while its residence time is 20 seconds in the evaporator. Hence it is suitable for heat sensitive materials.

(4) Unlike short tube evaporator, the tubes are not submerged. So there is no elevation of boiling point due to hydrostatic head.

(5) It is suitable for foam-forming liquids, because foam can be broken by an entrainment separator.

(6) It requires low hold up and small floor space.

Disadvantages : (1) Climbing film evaporator is expensive, construction is quite complicated.

(2) It is difficult to clean and maintain.

(3) Large head space is required.

(4) It is not advisable for very viscous liquids, salting liquids and scaling liquids.

(5) If feed rate is high, the liquor may be concentrated insufficiently. If feed rate is low, film cannot be maintained. Dry patches may form on the tube walls.

Falling Film Evaporator

Principle : In a falling film evaporator, feed enters from the top and flows down the walls of the tubes. The liquid gets heated rapidly due to heat transfer from steam. The liquid boils and becomes vapour, which forms small bubbles. They tend to fuse to form layers of bubbles, which travel down the tubes. Concentration takes place during this downward journey. Vapour and liquid are separated at the bottom.

Construction : The construction of a falling film evaporator is shown in Figure 6-6. It resembles climbing film evaporator, but is inverted. In this evaporator, the heating unit consists of steam jacketed tubes. The feed inlet is from the top of the steam compartment. The other provisions are steam inlet, vent and condensate outlet remain same. The outlet for the product is provided at the bottom and is connected to a cyclone separator.

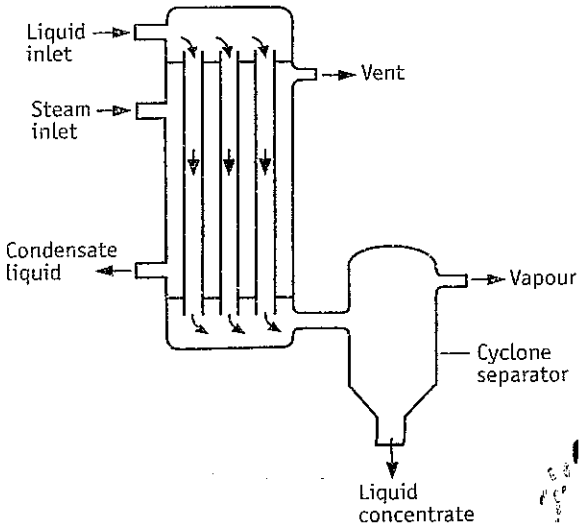


Figure 6-6. Falling film evaporator.

Working : Steam is supplied into the steam compartment. Feed enters from the top of the tubes. The temperature of the boiling liquid is same as that of the vapour head. The feed flows down the walls of the tubes. The liquid gets heated rapidly. The liquid boils and becomes vapour, which forms smaller bubbles. These tend to fuse to form layers of bubbles, which travel down the tubes. Concentration takes place during this downward journey. Vapour and liquid are separated in the cyclone separator.

Uses : Falling film evaporator is used to separate volatile and non-volatile materials, when the feed is of high viscosity. It is used for the concentration of yeast extract, manufacture of gelatin, extracts of tea and coffee. It is also useful for concentrating the heat sensitive materials such as fruit juices.

Advantages : (1) Falling film evaporator is suitable for high viscous liquids, because the flow of vapour film is assisted by gravity.

(2) The liquid hold-up is less and hold-up time is very small.

(3) The liquid is not overheated during passage and heat transfer coefficients are high even at low boiling temperature.

(4) Highly acidic and corrosive feeds can be concentrated using impervious graphite tubes and rubber lined vapour heads.

Disadvantages : Easy distribution of feed to the individual tubes may be accomplished using a perforated plate above the tubes or using spray nozzles. Hence, it is not suitable for suspensions, as the solids clog the perforated plate. It is not suitable for salting or scaling liquids. The feed distribution in the tubes is poor. For continuous supply, the liquid may be recirculated or the ratio of feed to evaporation is kept high.

Forced Circulation Evaporator

Principle : In forced circulation evaporator, liquid is circulated through the tubes at high pressures by means of a pump. Hence, boiling does not take place because boiling point is elevated. Forced circulation of the liquid also creates some form of agitation. When the liquid leaves the tubes and enters the vapour head, pressure falls suddenly. This leads to the flashing of super heated liquor. Thus evaporation is effected.

Construction : The construction of a forced circulation evaporator is shown in Figure 6-7. The steam jacketed tubes are held between two tube sheets. The tube measures 0.1 m inside diameter and 2.5 m long. The part of the tubes projects into the vapour head (flash chamber), which consists of a deflector. The vapour head is connected to a return pipe, which runs downwards and enters into the inlet of a pump.

Working : Steam is introduced into calandria. Pump sends the liquid to the tubes with a positive velocity. As the liquid moves up through the

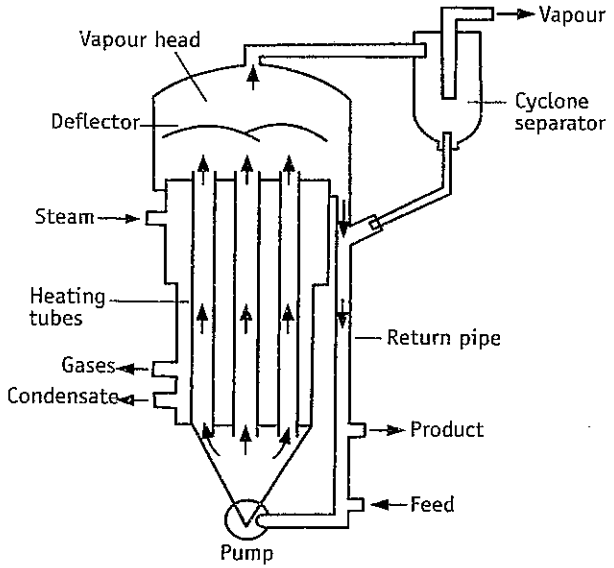


Figure 6-7. Forced circulation evaporator.

tubes, it gets heated and begins to boil. As a result, the vapour and liquid mixture rushes out of the tubes at a high velocity. This mixture strikes the deflector, which throws the liquid downward. This results in an effective separation of liquid and vapour. The vapour enters the cyclone separator and leaves the equipment. The concentrated liquid returns to the pump for further evaporation. Finally the concentrated product is collected.

Uses : If evaporation is conducted under reduced pressure, forced circulation evaporator is suitable for thermolabile substances. This method is used for the concentration of insulin and liver extracts. It is well suited for crystallizing operations where crystals are to be suspended at all times.

Advantages : (1) In forced circulation evaporator, the heat transfer coefficient is high due to rapid liquid movement.

(2) Salting, scaling and fouling are not possible due to forced circulation.

(3) This evaporator is suitable for thermolabile substances because of rapid evaporation.

(4) It is suitable for high viscous preparations because pumping mechanism is used.

Disadvantages : In forced circulation evaporator, the hold-up of liquid is high. The equipment is expensive, because power (pump) is required for circulating the liquid.

Comment 6-5. Heat sensitive products cannot be concentrated by pan evaporator? True or false. Explain.

Comment 6-6. Explain the basis for selecting copper and steel, respectively, as materials of construction for kettle and jacket of an evaporating pan?

Comment 6-7. What is the modification done in the heating compartment to increase the rate of evaporation?

Comment 6-8. What is the function of a deflector in an evaporator of climbing film/forced circulation type?

Comment 6-9. Climbing film evaporator is suitable for high viscosity liquids? True or false. Explain.

THEORY

In an evaporator, heat is transferred to the evaporating liquid so as to provide latent heat of vaporisation. Generally, steam is used as a source of heat. Several heat exchangers have been discussed in Chapter 5 'Flow of Heat'. Normally, tube and shell heat exchangers are used for heat transfer.

The amount of heat, which must be transferred through the walls of a calandria, varies with the nature of the liquid to be evaporated. The liquids used in pharmacy practice are water and hydroalcoholic solutions with low solid content. In case of bulk drugs, organic solvents are also used.

Evaporator Capacity

The total amount of heat required can be obtained by considering a simple diagram of an evaporator as shown in Figure 6-8.

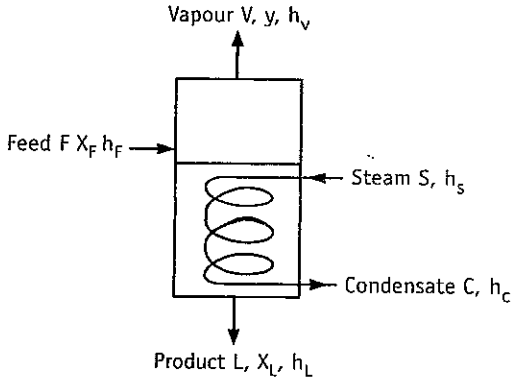


Figure 6-8. Evaporator system with its parameters.

Feed and steam are admitted into the evaporator. By consuming heat, the feed undergoes evaporation to form vapour, which will be allowed to escape. The concentrated product will be collected at its bottom. Simultaneously steam looses its heat energy and undergoes condensation, the condensate of which will be removed.

- Let F kg be the feed per hour to the evaporator, whose solid content is X_F (weight fraction) and enthalpy is h_F J/kg.
- Let L kg be the product collected per hour from an evaporator, whose solute composition is X_L (weight fraction) and enthalpy is h_L J/kg.
- Let V kg be the vapour liberated per hour from an evaporator, whose solute composition is y (weight fraction) and enthalpy is h_V J/kg. In most evaporators, the vapour is pure water as there is no entrainment and therefore y is zero.

Material Balancing

The material balance can be obtained from total material entering and total material leaving. It can be represented by an equation for the evaporation process.

$$\text{Feed (kg)} = \text{product collected (kg)} + \text{vapour liberated (kg)}$$

$$F = L + V \qquad ...(1)$$

Equation (1) can also be written for material balancing in terms of mass x weight fraction for the solute as:

$$FX_F = LX_L + Vy \qquad ...(2)$$

Energy Balancing

Steam is supplied for evaporation. Let S kg be the steam supplied per hour with an enthalpy of h_S J/kg. Let C kg be the condensate removed having an enthalpy of h_C J/kg. The heat balance can be obtained from total heat entering and total heat leaving. It can be represented by equation (3).

$$\text{Heat entering (J)} = \text{Heat leaving (J)} \qquad ...(3)$$

Equation (3) can also be written as:

$$\text{Heat in feed + heat in steam} = \text{Heat in thick liquor (product) + heat in vapour + heat in condensate + heat lost by radiation} \qquad ...(4)$$

Loss of heat by radiation is less and can be neglected. The equation (4) can also be written in terms of mass x enthalpy as:

$$Fh_F + Sh_S = Lh_L + Vh_V + Ch_C \qquad ...(5)$$

Temperature difference is the difference between the saturation temperature of the steam and the boiling point of the liquid. Generally, a temperature difference of *20 to 30 °C is sufficient for rapid evaporation of* solution. But in practice, the feed may have the temperature less than boiling point of the liquid. The steam may be superheated and the condensate may get cooled. All these factors influence evaporator calculation with respect to mass balance.

Improving Heat Transfer Coefficients

Evaporator is considered as a heat exchanger. Like any heat exchanger, heat is transferred from steam to the product. The general equation for heat transfer can be expressed by equation (6)

$$Q = UA\Delta t \qquad ...(6)$$

where Q = rate of heat transfer, W
U = overall heat transfer coefficient, W/m^2 K
A = heating surface area, m^2
Δt = temperature difference, K

Equation (6) can be used to determine the Q.

Heating surface (A in equation 6) must be large. For this purpose more number of tubes are mounted in parallel to form a unit known as calandria. The overall heat transfer coefficient, U, can be regarded as follows.

- Fluid film coefficient on steam side – always relatively higher.
- Thermal resistance of the metal wall – neglected because it is small.
- Fluid film coefficient on the liquid side – low, major determinant in heat transfer.

The overall coefficient (U) is approximately nearer to the lowest surface coefficient of the film. Any factor that improves the coefficient on the boiling side increases the overall coefficient almost proportionally. Some of the factors affecting these coefficients are:

Steam side – film coefficients can be increased	*Boiling liquid side–surface coefficient can be increased*
Temperature drop should be large	increasing the velocity by pumping the liquid
High temperature at which condensation takes place	decreasing the viscosity by feeding hot liquid
Amount of non-condensed gas in steam should be minimum.	cleaning of the heating surface

Pumping liquids at high velocities (forced circulation) through the tubes has beneficial effect. Such high velocities tend to decrease the thickness of the viscous film and the buffer layer.

Overall coefficients may be seriously lowered because of—

- corrosion of the surfaces.
- deposition of solid material from the evaporating liquid.
- The presence of noncondensable gases in the heating steam (air).

Efforts should be made to prevent the above effects. Forced circulation is an important measure, i.e. increase the velocity of liquid flow to increase the capacity of the evaporator.

MULTIPLE EFFECT EVAPORATOR

Vertical tube evaporator discussed earlier is a single effect evaporator (Figure 6-4). Such evaporators are connected in several ways so as to achieve large scale evaporation as well as greater economy. Although multiple effect evaporators are not used in the pharmaceutical industry, the principles are of interest and should be understood. This is illustrated using an example of triple effect evaporator with a parallel feed mechanism.

Advantages:

(1) It is suitable for large scale and for continuous operation.

(2) It is highly economical when compared with single effect.

(3) About 5 evaporators can be attached.

Construction : The construction of a multiple effect evaporator is shown in Figure 6-9 using 3 evaporators, i.e. triple effect evaporator. The other aspects of construction of vertical tube evaporator remain same as mentioned earlier. A perusal to Figure 6-9 indicates that the vapour from first evaporator serves as a heating medium for the 2nd evaporator. Similarly, vapour from 2nd evaporator serves as a heating medium for the 3rd evaporator. Last evaporator is connected to a vacuum pump.

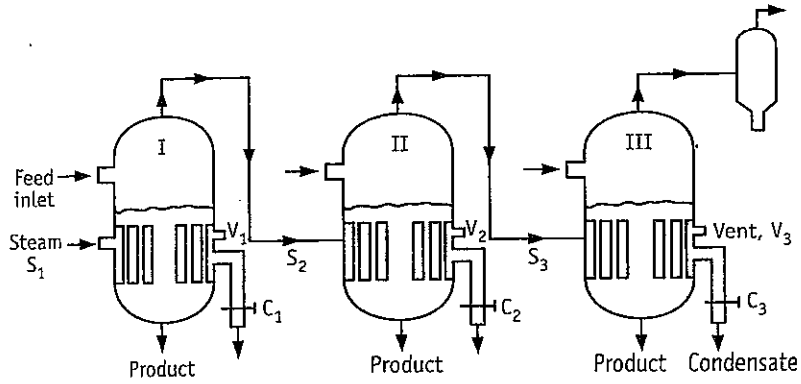


Figure 6-9. Triple effect evaporator with parallel feed arrangements.

Working : Parallel feed arrangement is used in this example.

Parallel feed : In this method, a hot saturated solution of the feed is directly fed to each of the three effects (evaporation) in parallel without transferring the material from one effect to the other. The parallel feed arrangement is commonly used in the concentration of salt solutions, where the solute crystallizes on concentration without increasing the viscosity.

Operations : In the beginning, the equipment is at room temperature and atmospheric pressure. The liquid feed is introduced to all the three

evaporators up to the level of the upper tube sheets. The following operations are attempted to achieve the effects as specified below.

1. The vent valves V_1, V_2 and V_3 are kept open and all other valves are closed (not shown in Figure 6-8).
2. Now a high vacuum is created in the liquid chambers of evaporators.
3. The steam valve S_1 and condensate valve C_1 are opened. Steam is supplied. Steam first replaces cold air in the steam space of 1st evaporator. When all the cold air is removed, the valve, V_1 is closed.
4. The supply of steam is continued until the desired pressure P_0 is created in the steam space of 1st evaporator. At this pressure, the temperature of the steam is t_0.
5. Steam gives its temperature to the liquid feed in the 1st evaporator and gets condensed. Condensate is removed through the valve C_1.
6. Due to heat transfer, the liquid temperature increases and reaches the boiling point. During this process, vapour will be generated from the liquid feed.
7. So formed vapour displaces air in the upper part of 1st evaporator. Moreover, the vapour also displaces the air in the steam space of the 2nd evaporator.
8. After complete displacement of air by vapour in the steam compartment of 2nd evaporator, the valve V_2 is closed.
9. The vapour of 1st evaporator transmits its heat to the liquid of 2nd evaporator and gets condensed. Condensate is removed through the valve C_2. These steps continue in the 3rd evaporator also.

As the liquid in the 1st evaporator gains temperature, the difference in temperatures between the liquid and steam decreases, hence, the rate of condensation decreases. As a result, the pressure in the vapour space of 1st evaporator gradually increases to P_1 by increasing temperature to t_1, which is the boiling point of the liquid in 1st evaporator, and decreasing the temperature difference $(t_0 - t_1)$.

A similar change takes place in the 2nd evaporator and the liquid reaches the boiling point. Similarly, the process will be repeated in 3rd evaporator. Finally three evaporators (or effects as they are called) come to a steady state with the liquid boiling in all the three bodies.

As boiling proceeds, liquid level in 1st evaporator comes down. Feed is introduced through the feed valve to maintain the liquid level constant. Similarly evaporation of liquid takes place in 2nd and 3rd evaporators. To maintain liquid levels constant, feed valves F_2 and F_3 are used for 2nd and

3rd evaporators, respectively. This process is continued until the liquid in all the evaporators reaches the desired viscosity.

Now the product valves are opened to collect the thick liquid. Thus in this evaporator, there is a continuous supply of feed, continuous supply of steam and continuous withdrawal of liquid from all the three evaporators. Hence, evaporator works continuously with all the temperatures and pressures in balance.

The evaporator can also be fed by forward feed method, backward feed method and mixed feed method. In the forward feed method, the mother liquor is introduced into 1st then transferred to 2nd and then to 3rd. In the backward feed method, the mother liquor is introduced into the 3rd evaporator, then transferred to 2nd and then transferred to 1st. In mixed feed method, the mother liquor is introduced into 2nd evaporator then transferred to 3rd evaporator and then transferred to 1st evaporator.

Economy of Multiple Effect Evaporator

The economy of an evaporator is the quantity of vapour produced per unit steam admitted. It is calculated by considering the following assumptions.

Feed is admitted at its boiling point. Therefore, it does not require any more heat to raise its temperature. Hence, the supplied steam gets condensed to give heat of condensation. This heat will then be transferred completely to the liquid. The heat transferred now serves as latent heat of vaporisation, i.e. liquid undergoes vaporisation by receiving heat. Loss of heat by any means is negligible.

The economy of an evaporator may be expressed as:

$$\text{Economy of an evaporator} = \frac{\text{total mass of vapour produced}}{\text{total mass of steam supplied}}$$

In single effect evaporator, steam produces vapour only once. Hence,

$$\text{Economy of a single effect evaporator} = \frac{\text{N units of vapour produced}}{\text{N units of steam supplied}} = 1$$

In multiple effect evaporator, one unit of steam produces vapour many times, depending on the number of evaporators connected. Hence,

$$\text{Economy of multiple effect evaporator} = \frac{\text{N units of vapour produced}}{\text{1 units of steam supplied}} = N$$

Therefore, economy of multiple effect evaporator is N times the economy of the single effect evaporator. However, such a great economy is approximately true as it depends on many factors such as temperature of the feed, temperature range in the evaporator, ratio of weight of feed to the product and pressure difference.

Comment 6-10. The economy of multiple-effect evaporator is higher than that of the single-effect evaporator. Justify.

Summary

Evaporation is a process of vapourizing large quantities of volatile liquid to obtain a product of a concentrated fluid. The feed is a solution or a suspension which is obtained from extraction or bulk drug production. If the volatile liquid is water, it can be left into atmosphere. If the liquid is an organic solvent, then solvents is removed in a closed process, so as to ensure economy and environmental safety. Evaporation is a surface phenomenon and boiling does not occur. Thus evaporation is a slow and often the solvent is removed by boiling the liquid. This step has become an operational necessity. The latent heat of vapourization is provided and normally steam is used as a source of heat. Evaporation is a downstream operation and the next operation is usually crystallization or drying. Evaporation unit operation is essential in the manufacture of bulk drugs, manufacture of biological products, etc. Several factors are considered in order to increase the rate of evaporation. A few factors are; temperature, vapour pressure, surface area, moisture content of the feed, type of product required, time of evaporation, etc. The rate of evaporation is controlled by the rate heat transfer.

Steam jacketed kettle with an open pan is a simple form of equipment. It is suitable for concentrating aqueous and thermostable liquors. This procedure is not economical. Horizontal tube evaporator uses the heat exchanger. In general, evaporator is a cylindrical body with a conical (or dome) shaped top and bottom. Heat transfer takes place through the tubes, liquid outside the tubes gets heated and the vapour leaves the evaporator from the top. The concentrated liquid is collected from the bottom. Horizontal tube evaporator is suitable for non-viscous solutions that do not deposit scales. The vertical tube evaporator is used in the manufacture of sugar, salt, caustic soda and cascara extract. The heating mode remains the same except the vertically placed tubes. The liquid inside the tubes get heated and the vapour leaves the evaporator from the top. A cyclone separator is included for separation of the vapour and liquid concentrate. Climbing film evaporator, the preheated feed enters from the bottom and flows up through the heated tubes. In this process, the liquid near the wall gets vapourized and forms small bubbles. These tend to fuse into large bubbles, which travel up on the walls along with entrapped slug. The liquid films are blown up from the top of the tubes and strikes entrained separator (deflector) kept above. The liquid concentrate is thrown down into

the lower part from where the product is withdrawn. In the falling film evaporators, the feed enters from the top. The concentrate is collected from the bottom. For this separation, a cyclone separator is included. It is used for the concentration of yeast extract and manufacture of gelatin. Forced circulation evaporator is used for the concentration of insulin and liver extracts. Forced circulation of the liquid also promotes some form of agitation. When the liquid leaves the tubes and enters the vapour head, pressure falls suddenly. This leads to the flashing of superheated liquid. The velocity of liquid flow is increased to increase the capacity of the evaporator. A cyclone separator is included. In several situations, multiple-effect evaporator is employed, because of its fairly high economy. In this case, the vapour of first evaporator serves as a heating medium for the 2^{nd} evaporator. Similarly, the vapour of 2^{nd} evaporator serves as a heating medium for the 3^{rd} evaporator. Last evaporator is connected to a vacuum pump. Thus economy is achieved. The critical attributes of quality for the evaporation are: temperature of the feed, temperature of the evaporator, ratio of weight of feed to product and the pressure difference.

Glossary of Symbols

- b = Maximum vapour pressure at the temperature of air, kPa.
- b′ = Pressure due to the vapour of the liquid actually present in the air, kPa.
- C = Amount of condensate removed, kg.
- F = Amount of feed, kg.
- h_C = Enthalpy of the condensate, J/kg.
- h_F = Enthalpy of the feed, J/kg.
- h_L = Enthalpy of the product concentrate, J/kg.
- h_S = Enthalpy of the steam, J/kg.
- h_V = Enthalpy of the vapour, J/kg.
- K = Constant. m/s.
- L = Mass of product collected from evaporator, kg.
- M = Mass of vapour formed per unit time, m^3/s.
- p = Atmospheric pressure, kPa.
- Q = Rate of heat transfer, W.
- S = Amount of steam introduced, kg.
- S = Surface area of the liquid exposed, m^2.
- Δt = Temperature difference. °K.
- XF = Solid content in the feed (weight fraction).
- XL = Solute composition in the product (weight fraction).
- U = Overall heat transfer coefficient, W/m^2. K.
- V = Amount of vapour liberated, kg.
- y = Solute composition in vapour, (weight fraction).

QUESTION BANK

Each question carries one mark

Note : Encircle the alphabet which corresponds to the single best response.

1. Which one of the following conditions is correct for evaporation?
   A. Constituents must be thermolabile
   B. Liquid must be viscous
   C. Solvent must be non-volatile
   D. Solvent must be volatile
2. In climbing film evaporator, the problem in evaporation is:
   A. boiling point of liquid B. droplet formation
   C. entrainment of liquid D. film formation
3. Which is the factor that does NOT influence the rate of evaporation?
   A. Difference in vapour pressure
   B. Melting point of solids
   C. Surface area of the evaporator
   D. Viscosity of the solution
4. Which condition of evaporation is used for the production of malt extract?
   A. Atmospheric pressure B. High pressure
   C. Normal pressure D. Reduced pressure
5. Dry extract of belladona is prepared by exposing the material to one of the following conditions.
   A. First to higher temperature and then to lower temperature
   B. First to lower temperature and then to higher temperature
   C. Higher temperature
   D. Lower temperature
6. Which type of equipment gives porous on evaporation?
   A. Film evaporator B. Multiple effect evaporator
   C. Open pan evaporator D. Vacuum evaporator
7. Calendria consists of a number of:
   A. baffles B. jackets
   C. outlets D. tubular surfaces
8. Which is the operation subsequent to evaporation?
   A. Crystallisation B. Distillation
   C. Drying D. Extraction
9. Steam side film coefficients are increased by one of the following methods.
   A. Condensing liquid at low temperature
   B. Decreasing the velocity of liquid
   C. Non-condensed gas in steam should be minimum
   D. Temperature drop should be small

10. The cost per square metre of heating surface is usually high in one of the evaporators.
    A. Horizontal tube evaporator B. Falling film evaporator
    C. Steam jacketed kettle D. Vertical tube evaporator
11. Which evaporator is used to concentrate insulin, liver extract and vitamins?
    A. Climbing film evaporator B. Falling film evaporator
    C. Horizontal tube evaporator D. Vertical tube evaporator
12. In climbing film evaporator, what is the purpose of the entrainment separator?
    A. Allowing the heat to transfer B. Allowing the vapour to escape
    C. Breaking the foam D. Pulling the liquid up
13. In equation, $Q = UA\Delta t$, U is overall heat transfer coefficient and its units are:
    A. $W/m^2 \times K$ B. $W/m \times K^2$
    C. $m^2 \times K/W$ D. $m \times K^2/W$
14. What is the source of heat in most of the evaporators?
    A. Coal B. Hot water
    C. Oil bath D. Steam
15. In which type of evaporator, the formation of vapour film is assisted by gravity?
    A. Climbing film evaporator B. Falling film evaporator
    C. Horizontal film evaporator D. Multiple effect evaporator
16. From the following, select the one that forms scales in an evaporator.
    A. Benzoic acid B. Calcium sulphate
    C. Salicylic acid D. Sodium chloride
17. Pick a suitable evaporator also helps in growing of coarse crystals.
    A. Forced circulation evaporator B. Long tube vertical evaporator
    C. Multiple effect evaporator D. Short tube vertical evaporator
18. Triple effect evaporator uses one of the following types of evaporator?
    A. Climbing film evaporator B. Falling film evaporator
    C. Horizontal tube evaporator D. Vertical tube evaporator
19. Which one of the following is more heat sensitive during evaporation?
    A. Alkaloids B. Glycosides
    C. Hormones D. Volatile oils
20. Which type of evaporator is suitable for thermolabile substances and highly viscous preparations?
    A. Forced circulation evaporator B. Horizontal tube evaporator
    C. Short tube vertical evaporator D. Steam jacketed kettle

21. Which one of the following factors increases the efficiency of evaporator?
    A. High moisture content B. High velocity flow
    C. High viscosity of liquid D. High volume of liquid
22. For calculation of mass transfer, which one of these aspects is essential?
    A. Condensate must also be collected
    B. Electrical heating
    C. Feed temperature must be higher than steam
    D. Steam heating
23. Select the preferable evaporator suitable for corrosive liquid that gives a crystalline product.
    A. Falling film evaporator B. Forced circulation evaporator
    C. Horizontal film evaporator D. Vertical tube evaporator
24. Normally evaporation process is carried out at one of the following experimental conditions.
    A. Above the boiling temperature
    B. At the boiling temperature
    C. Below the boiling temperature
    D. Room temperature
25. What is the purpose of a deflector in a forced circulation evaporator?
    A. Creates large surface area
    B. Facilitates pumping of liquid
    C. Promotes separation of liquid and vapour
    D. Provides heat to the evaporator
26. Preheated feed enters into one of the following evaporators?
    A. Evaporating pan B. Falling film type
    C. Horizontal tube D. Rising film type
27. In which method, the feed enters the last effect and moves from 3rd to 1st and 2nd?
    A. Backward feed B. Forward feed
    C. Mixed feed D. Parallel feed

Each question carries 2 marks

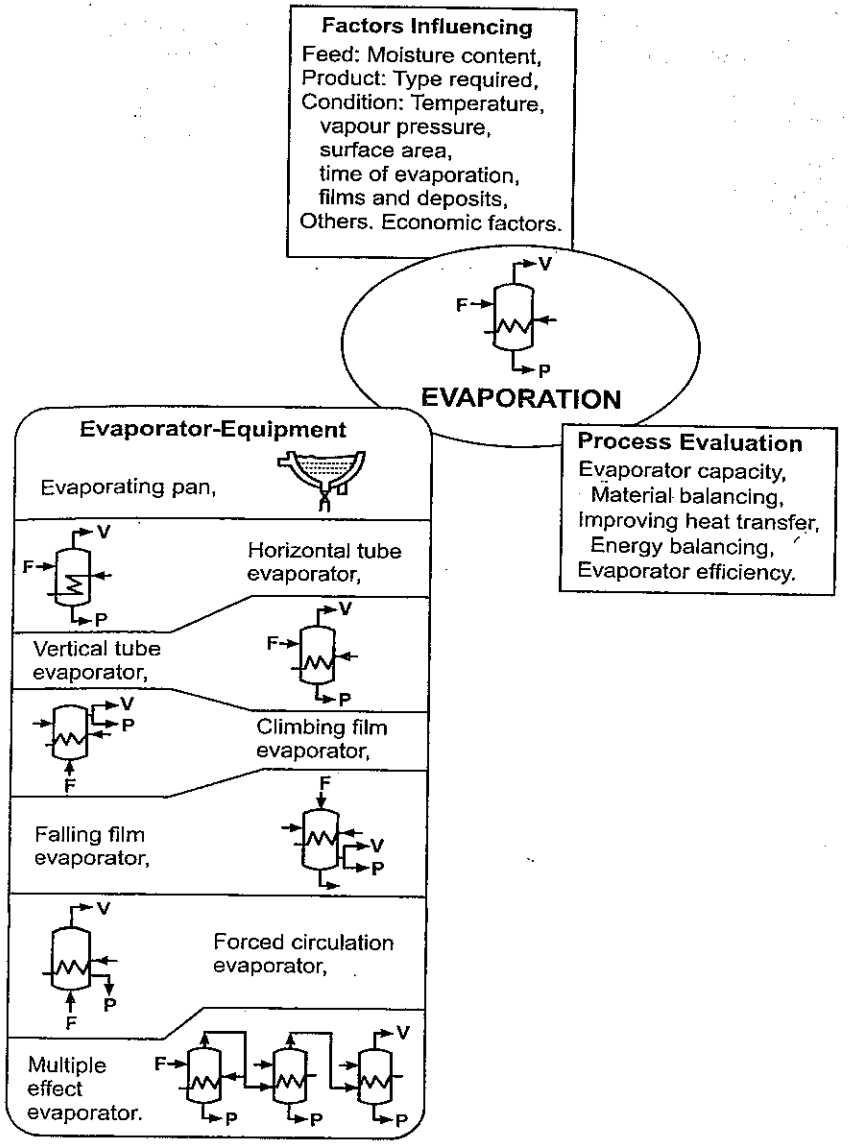
1. Explain the term Evaporator capacity.
2. Define evaporation in terms of capacity and economy as applied to evaporation practice.
3. Explain the construction of calandria. Give its uses.

Each question carries 5 marks

1. Elaborate the concept of multiple effect evaporation. What specific advantages does it offer?
2. Describe the construction and working of film evaporator of any one type.
3. Explain the construction and working of a forced circulation evaporator.

Each question carries 10 marks

1. How do film evaporator function? Elaborate the answer with a neat sketch of one such evaporator. List the merits and demerits of film evaporator system.
2. Classify evaporators. Describe construction and working of a film evaporator.
3. Explain the terms 'multiple effect evaporation' and 'evaporator capacity'. How many effects generally go into a multiple effect evaporator?
4. What do you understand by 'multiple effect evaporator'? Describe one such evaporator. How do you feed such evaporator?



MINDMAP OF EVAPORATION UNIT OPERATION

CHAPTER 7

Distillation

Theory
General Equipment for Distillation
Classification of Distillation Methods
Simple Distillation
Flash Distillation
Fractional Distillation
Azeotropic and Extractive Distillation
Distillation under Reduced Pressure
Steam Distillation
Molecular Distillation
Destructive Distillation
Compression Distillation

LEARNING OBJECTIVES

After reading this chapter, the reader should be able to:

- Appreciate the principles of distillation with applications.
- Understand the basic laws governing the behaviour of liquids.
- Explain the basic necessities for arranging distillation apparatus based on the properties of materials.
- Explain the designs of distillation equipment of various types with working and uses.
- Select a suitable distillation method based on the properties of the materials.

Distillation is defined as the separation of the components of a liquid mixture by a process involving vaporization and subsequent condensation at another place.

The distillation process involves two steps; (a) converting a liquid into vapour phase and (b) transferring the vapour to another place and recovering the liquid by condensation. The feed liquid is known as *distilland*. The condensed liquid is known as *distillate* or *condensate*.

If one component is volatile and others are non-volatile, it is possible to separate volatile components from non-volatile components by distillation. In such cases, distillation is considered as a separation or purification

method. When heat is supplied to a mixture, a more volatile liquid evaporates readily than the less volatile liquid. As a result, the condensed liquid consists of a high proportion of highly volatile liquid and less amount of less-volatile liquid. Therefore, distillation is said to be *partial separation method*. The extent of separation is governed by the properties of the components involved and the physical arrangements used for distillation.

In practice, it is difficult to distinguish three processes, namely evaporation, distillation and drying. Only working definitions help in differentiating them.

1. *Distillation* operation is used when condensed vapour is required as a product.
2. *Evaporation* operation is used when the concentrated liquid residue is needed as a product. The temperature of the liquid is maintained below its boiling point. Further vapour is not condensed, unless recovery is essential.
3. *Drying* operation is used when dried solid residue is required as a product.

Applications

Separation of volatile oils : Volatile oils are separated from cloves, anise seeds and eucalyptus leaves by the method of steam distillation.

Purification of organic solvents : Normally, simple distillation method is used for the purification of liquids having single component as a major fraction. Simple distillation method is also used for determining the boiling range of a liquid as per IP, 1996, as a method to decide the purity. Absolute alcohol (100 % ethanol) can be obtained by azeotropic distillation.

Manufacture of official preparations : Spirit of nitrous ether and aromatic spirit of ammonia are prepared by simple distillation. Distilled water and water for injection are prepared as per the specifications of pharmacopoeia by simple and compression distillation methods.

Refining of petroleum products : In the petroleum industry, the crude oil is refined into different fractions using flash distillation. Each fraction is a multicomponent system. E.g. petroleum ether 60 and 80.

Recovery of solvents : Solvents are used for extraction of drugs from plant parts and synthetic reaction mixtures. These solvents must be recovered, in order to prevent environmental contamination. The recovered solvent may be recycled for further use.

Quality control methods : Distillation method is used for determining alcohol content in liquid dosage forms such as elixirs, as per IP, 1996. Azeotropic distillation method is used for the determination of water content in a substance using toluene according to IP, 1996.

Separation of drugs obtained from plant and animal sources : Drugs of natural origin (such as plants) are normally extracted using maceration or percolation methods. The menstruum (solvent) used for extraction is distilled off and the active constituents are separated. For example, vitamin A is separated from fish liver oil using the method of molecular distillation.

Purification of drugs obtained from chemical process : Many chemical processes involve the conversion of raw materials into products. The products are separated from the reaction mixture and purified using the methods of distillation.

In order to handle distillation effectively and economically, it is necessary to understand the theory behind this process. Several variables are involved in the process, which are often interrelated. Theory includes the understanding of different factors influencing the distillation process. The laws of conservation of matter and conservation of energy have to be applied. This chapter deals with the theory, methods and types of equipment involved in the distillation process.

Comment 7-1. Is the distillation a separation process or an extraction process? Explain.

THEORY

Distillation is a process of separating and purifying the components in a liquid mixture. The primary data required to solve any distillation problem are vapour-liquid equilibrium relationship. Distillation method depends on the relative volatilities of the components present in the mixture. Some of these aspects are discussed below.

When two liquids are mixed together, they may be miscible with each other in all proportions. Such miscible liquids are known as *binary mixtures* of liquids.

Examples of binary mixtures are ethyl alcohol and water, water and acetone, benzene and carbon tetrachloride. It is essential to understand theories of ideal and real solutions (non-ideal).

Ideal Solutions

Ideal solution is defined as the one in which there is no change in the properties of the components other than dilution, when they are mixed to form a solution.

Heat is neither absorbed nor evolved during mixing. The final volume of the solution represents the additive property of the individual constituents. Example is methanol and water, which have similar properties. Ideal solution theory provides a model system to which real or non-ideal solutions can be compared. Ideal solutions are characterised by one of the important physicochemical properties of liquids namely vapour pressure.

Raoult's Law

Raoult's law expresses a quantitative relationship between the concentration and vapour pressure.

Raoult's law states that the partial vapour pressure of each volatile constituent is equal to the vapour pressure of the pure constituent multiplied by its mole fraction in the solution at a given temperature.

Since the solution is homogeneous by definition, the relative numbers of components on the surface reflect the numbers of these components in the whole of solution. These numbers can be expressed on mole fraction scale. Thus Raoult's law is appropriately suited to describe an ideal solution.

Consider a mixture of miscible liquids A and B. In this mixture:

Let partial vapour pressure exerted by $A = p_A$ kPa.

Let partial vapour pressure exerted by $B = p_B$ kPa.

Let vapour pressure exerted by the pure component, $A = p_A^o$ kPa.

Let vapour pressure exerted by the pure component, $B = p_B^o$ kPa.

Let mole fraction concentration of liquid, $A = X_A$

Let mole fraction concentration of liquid, $B = X_B$

Raoult's law may be mathematically expressed as:

Partial vapour pressure of a liquid = vapour pressur of pure liquid × mole fraction of the liquid

$$p_A = p^oA\,X_A \quad \ldots(1)$$

$$p_B = p^oB\,X_B \quad \ldots(2)$$

A mixture of ethylene chloride and benzene obeys Raoult's law. When two liquids are mixed, the vapour pressure of each one is reduced by the presence of other to the extent of dilution of each phase.

Ideal solution is defined as the one that obeys Raoult's law. Raoult's law is obeyed by only a few solutions of liquid in liquids. These solutions are also known as *'perfect' solutions*. The components of these solutions have a similar structure. Examples are benzene and toluene, *n*-hexane and *n*-heptane, ethyl bromide and ethyl iodide. The individual components do not have interaction of any kind or complete uniformity of attractive forces is observed.

Dalton's Law

Dalton's law of partial vapour pressures states that the total pressure exerted by a mixture of ideal gases may be considered as sum of the partial vapour pressure exerted by each gas, if alone were present and occupied the total volume.

Dalton's law is mathematically expressed as:

Total vapour pressure = partial pressure of A + partial pressure of B

$$P = p_A + p_B \quad ...(3)$$

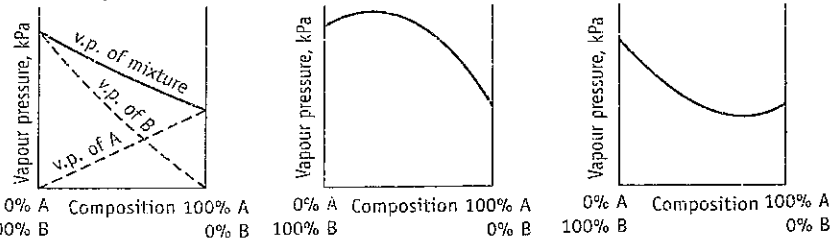
Substituting equations (1) and (2) in equation (3) gives

$$P = p_A^o X_A + p_B^o X_B \quad ...(4)$$

Their properties are additive, i.e. the total vapour pressure of the mixture is the weighted average of the vapour pressures of pure individual constituents. This behaviour is shown in Figure 7-1a. The following conclusions can be drawn from Figure 7-1a.

- The partial pressure of the component varies linearly from zero to full vapour pressure as the mole fraction varies from zero to one.
- The total pressure exerted by the system at a particular composition is equal to the sum of the partial pressures of its components.

Applications : According to an ideal solution, the component having relatively greater vapour pressure will be distilled first. This principle is used in simple distillation.



(a) Ideal curve- Raoult's Law (b) Positive deviation from Raoult's law (c) Negative deviation from Raoult's law

Figure 7-1. Vapour-composition diagrams for different liquid-liquid systems.

Real Solutions

Most systems show varying degree of deviation from Raoult's law, depending on the nature of the liquids and the temperature. These solutions are known as *real solutions*.

Deviations are observed because solute-solute, solvent-solute and solvent-solvent interactions are unequal. Examples include carbon tetrachloride and cyclohexane, and chloroform and acetone. Mutual interactions lead to either lowering or enhancing of the vapour pressure of the mixture with respect to ideal behaviour.

These are described as follows.

Positive deviation : In some liquid systems, the vapour pressure is greater than the sum of the partial pressures of the individual components. Such systems are said to exhibit *positive deviation from Raoult's law.*

Examples include carbon tetrachloride and cyclohexane, benzene and ethanol. The typical behaviour of such a system is shown in Fig. 7-1b. This type of behaviour occurs when the components differ in their polarity, length of hydrocarbon chain and degree of association. The degree of deviation from Raoult's law decreases as the temperature increases, since the differences in the nature of components are reduced at higher temperatures. Conversely a decrease in temperature may lead to a decrease in miscibility of two components and phase separation.

Negative deviation : In some liquid systems, the vapour pressure is lower than that of the sum of the partial pressures of the individual components. Such systems are said to exhibit *negative deviation from Raoult's law.*

Examples include chloroform and acetone, pyridine and acetic acid, water and nitric acid. The typical behaviour of such a system is shown in Figure 7-1c. This type of behaviour occurs, when interactions such as hydrogen bonding, salt formation and hydration occur between the components of a solution. As a result, the vapour pressure of each component is lowered with respect to the behaviour of an ideal solution. The total vapour pressure curve shows a minimum in the curve (Figure 7-1c).

Raoult's law does not apply over the entire concentration range in a non-ideal solution. If one liquid is present in high concentrations, it is considered as a solvent. The other liquid is very dilute. Hence, Raoult's law is valid for that composition, though the liquid pair behaves non-ideal manner.

Applications : The differences in the behaviour of a mixture influence the method of distillation. The areas include fractional distillation of intermediates and drugs, purification of alcohol and other organic solvents. Complete separation of the components of a mixture by fractional distillation may not be achieved if large positive or negative deviations from Raoult's law are observed. Such solutions form so-called azeotropic mixtures. Therefore, the principles of real solutions are important in distillation.

Volatility

The *volatility* of any substance in a solution may be defined as the equilibrium partial pressure of the substance in the vapour phase divided by the mole fraction of the substance in the solution.

For example, a substance A in a liquid mixture has partial pressure p_A and its concentration in the mixture is X_A on mole fraction scale. Then, volatility of A (v_A) may be mathematically expressed as:

Volatility of component A,

$$v_A = \frac{\text{partial vapour pressure of } A}{\text{mole fraction of } A \text{ in solution}} = \frac{p_A}{X_A} \quad ...(5)$$

The volatility of a material in the pure state is equal to the vapour pressure of the material.

Relative Volatility

Consider a liquid mixture containing two components A and B. In such a case, the volatility of one component is expressed in terms of the second. *Relative volatility* may be defined as:

$$\text{Relative volatility, } \alpha = \frac{\text{volatility of component } A}{\text{volatility of component } B} = \frac{v_A}{v_B} \quad ...(6)$$

Relative volatility is commonly expressed with the higher of the two volatilities in the numerator. This means that the relative volatility should never have a numerical value less than 1.0.

Since, $v = p/X$ (equation 5), it may be substituted in equation (6)

$$\alpha = \frac{p_A / X_A}{p_B / X_B} = \frac{p_A X_A}{p_B X_B} \quad ...(7)$$

According to Dalton's law, the partial vapour pressures of A and B may be expressed as:

$$p_A = Y_A . P \quad ...(8)$$

$$p_B = Y_B . P \quad ...(9)$$

where Y_A = mole fraction A in the vapour state

Y_B = mole fraction B in the vapour state

P = total pressure of the vapour, kPa

Relative volatility may also be expressed by substituting equations (8) and (9) in Equation (7) gives:

$$a_{AB} = \frac{Y_A P . X_B}{Y_B P . X_A} = \frac{Y_A P . X_B}{Y_B P . X_A} \quad ...(10)$$

Equation (10) often gives the definition of relative volatility.

Using equation (10), the value of relative volatility can be calculated directly from the vapour-liquid equilibrium data. For example, a mixture of methyl alcohol and water is having a total vapour pressure of 101.31 kPa (760 mmHg). This liquid contains 0.40 mole fraction of methyl alcohol and the equilibrium vapour contains 0.729 mole fraction. The data may be written as:

$$X_A = 0.4 \; ; \; Y_A = 0.729 \; ; \; X_B = 0.6 \; ; \; Y_B = 0.271.$$

$$\text{Relative volatility} = \frac{0.729 \times 0.60}{0.271 \times 0.40} = 4.035$$

Sometimes, relative volatility may change with concentration especially if the binary solution does not obey Raoult's law. However, mixtures obeying Raoult's law show only a slight change in relative volatility with concentration variation.

Comment 7-2. Is the Dalton's law applicable in the distillation process? Explain.

GENERAL EQUIPMENT FOR DISTILLATION

The construction of equipment for the distillation has been described using several figures in subsequent sections. The general equipment, either for laboratory use or for industrial scale, consists of three parts.

Still

It is a vaporizing chamber and used to place the material to be distilled. The size of the still should be such that only one-half to two-thirds full of liquid is filled. If the still is too large, superheating and some times decomposition of liquid may occur. The still is heated by a suitable means (e.g. steam) for the vaporisation of the volatile constituents. The temperature at which the liquid boils is of considerable importance. Therefore, provision is made to place the thermometer in the still. A condenser is attached to the still using appropriate joints.

On laboratory scale, round bottom flasks made of glass are used so that the progress of the distillation can be noticed. At the same time, the feed can be added as and when required. Stills are made of stainless steel, copper or suitable material to provide efficient heat transfer. In these stills, an observation window is provided.

Some liquids have a tendency to bump or froth, which promotes the carrying of liquid with vapour. To prevent this, a trap is inserted between distillation flask and condenser.

Condenser

Condenser helps in condensing the vapour. Condenser is a heat exchanger. It is kept cold by circulating water through water jacket. The boiling point and volatility of a substance are the main factors governing the choice of the condenser. The main points in the construction of a condenser are as follows.

1. The condenser must be easy to clean.
2. The cooling surface must be large enough, because rate of condensation is proportional to the area of the condensing surface.
3. The condensing surface must be reasonably a good conductor of heat, because rate of condensation is proportional to the rate at

which the surface is cooled. For this reason, metal condenser is preferred over glass, if suitable.

4. The film of condensed liquid is a bad conductor and must be removed quickly in order to avoid serious impairment of the efficiency of condenser. For this reason, condenser is always placed in an inclined position.
5. The warm water in contact with the condensing surface must be quickly carried away and its place should be taken by fresh cold water. The cooling water is arranged to move on the counter-current principle, i.e. its direction of flow is opposite to that of the flow of vapour to be condensed.

The condenser is connected to the receiver through a suitable adapter. *Adapter* may be employed where the receiver cannot be conveniently supported at the end of the condenser. Some times, the adapter has a provision to connect to the vacuum pump as in case of vacuum distillation. Condenser is placed in an upright or oblique position. Different types of condensers are used (Figure 7-2). Three classes of condensers are described below.

1. *Single-surface condensers* : Examples are Liebig condenser (Figure 7-2a), spiral (glass-worm condenser) (Figure 7-2b).
2. *Double-surface condensers* : The efficiency of the condensation increases. (Figure 7-2c).

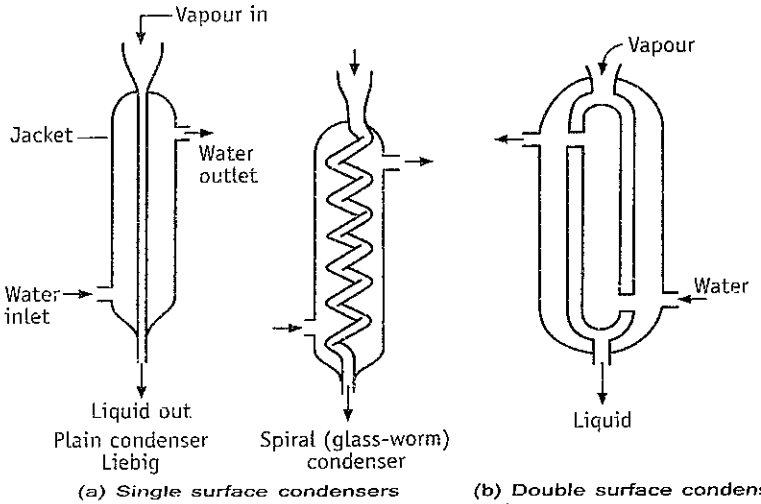


Figure 7-2. Different types of condensers.

3. *Multi-tubular condensers* : These are usually made of metal and used for large scale work. In the preparation of distilled water and water for injection, multi-tubular condensers are used.

The basic differences in the construction show variations in the efficiency of the condensation. Water-cooled condensers are not suitable for liquids, which boil above 130 °C. In such cases, *air condenser* may be used in place of water condenser. Air condenser is a straight tube with sufficient length (1-2 m long), which is passed through the bung of the flask. The vapour rises in the air-cooled tube and gets condensed.

Receiver

It is used to collect the distillate. It may be a simple flask (Figure 7-3a & b) or modified flasks such as Florentine receivers (Fig. 7-3c & d). Some

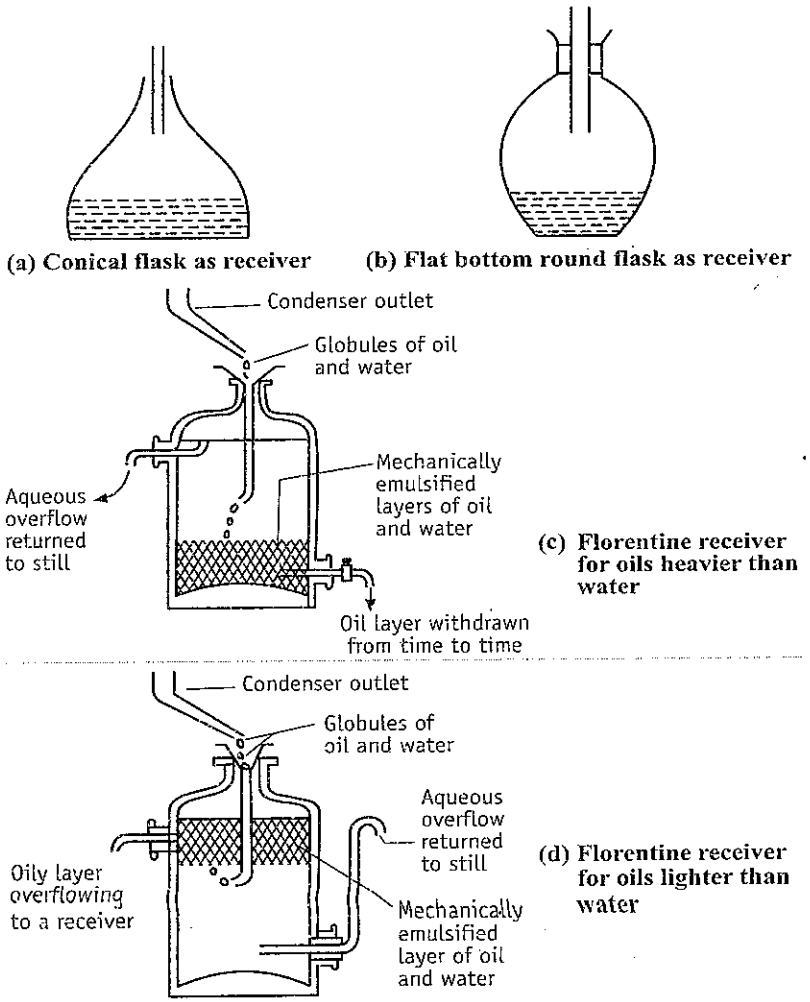


Figure 7-3. Different types of receivers.

times, the receiver is immersed in an ice-bath or any other freezing mixture. This minimizes loss of volatilization. Florentine receivers are used for the separation of oil and water. These are two types.

Type I : These are used for the separation of oil heavier than water.

Type II : These are used for the separation of oil lighter than water.

The receiver used for oil heavier than water has two taps (Figure 7-3c). The tap fitted near the bottom of vessel is used for collecting oil, while the tap fitted near the top of the vessel for water to overflow.

The receiver used for oil lighter than water is fitted with siphon at the bottom, which works when it gets filled with water (Figure 7-3d), while the tap fitted near the top is an outlet for the flow of oil.

Some times, the receiver is immersed in an ice-bath or any other freezing mixture. This minimizes loss due to volatilization.

Comment 7-3. What is the importance of the Florentine receiver?

CLASSIFICATION OF DISTILLATION METHODS

- Simple distillation
- Flash distillation
- Fractional distillation
- Azeotropic and extractive distillation
- Distillation under reduced pressure
- Steam distillation
- Molecular distillation
- Destructive distillation
- Compression distillation

Some of these methods are discussed in the following sections both on laboratory scale and industrial scale along with the specific theories.

Critical Quality Attributes – Distillation

The CQAs, process parameters (PPs) and material attributes (MAs) are recorded in Figure 7-4. The distillation is considered as a separation of components of liquid mixture or purification as is observed in the production of bulk drugs, process chemistry and biopharmaceutical products. The upstream operation is extraction and downstream operation is packing. For a given set of conditions, the critical attribute is the purity (assay) of the product.

The process parameters optimized for the distillation are: heating/cooling program. These are controlled during the distillation and are prefixed as standards with limits for a given set of conditions. Production control

charts are used for monitoring the standards. The above mentioned are the general characteristics, but a few may change depending on the method of distillation.

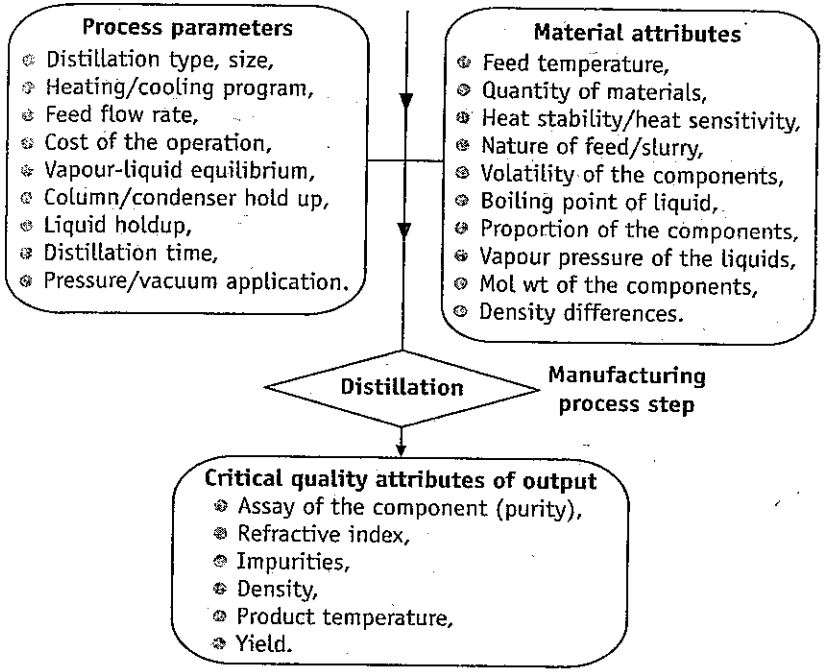


Figure 7-4. Process parameters and critical quality attributes for distillation in the separation of products from mixture.

SIMPLE DISTILLATION

Simple distillation is a process of converting a single constituent from a liquid (or mixture) into its vapour, transferring the vapour to another place and recovering the liquid by condensing the vapour, usually by allowing it to come in contact with a cold surface.

This process is known *differential distillation*, as distillation is based on the differences in volatilities and vapour pressures of the components in the mixture. This method requires simple apparatus.

Principle : Liquid boils when its vapour pressure is equal to atmospheric pressure. Simple distillation is conducted at its boiling point. The higher the relative volatility of a liquid, the better is the separation by simple distillation. Heat is supplied to the liquid so that it boils. The resulting vapour is transferred to a different place and condensed. If the liquid of interest is volatile and remaining components are nonvolatile, then simple distillation is a useful means of purification and separation of liquids.

Applications :

(1) Simple distillation is used for the preparation of distilled water and water for injection.

(2) Volatile and aromatic waters are prepared.

(3) Organic solvents are purified.

(4) A few official compounds are prepared by distillation. E.g. spirit of nitrous ether and aromatic spirit of ammonia.

(5) Non-volatile solids are separated from volatile liquids.

Laboratory Scale Apparatus for Distillation

Assembling of apparatus : The construction of a simple distillation apparatus is shown in Figure 7-5. It consists of a distillation flask with a side-arm sloping downwards. Condenser is fitted into the side arm by means of a cork. The condenser is usually water condenser, i.e. jacketed for circulation of water. The condenser is connected to a receiver flask using an adapter. On a laboratory scale, the whole apparatus is made of glass.

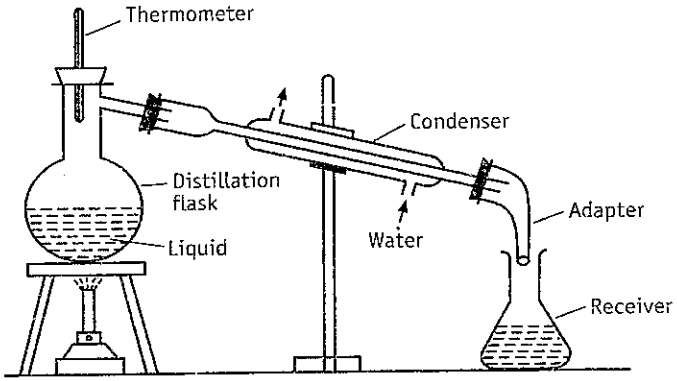


Figure 7-5. Apparatus for simple distillation (on laboratory scale).

Procedure : In the laboratory scale, the liquid to be distilled is filled into the flask to one-half to two-third of its volume. Bumping is avoided by adding small pieces of porcelain or porous pot before distillation. A thermometer is inserted into the cork and fixed to the flask. The thermometer bulb must be just below the level of the side arm. Water is circulated through the jacket of the condenser as shown in Figure 7-5.

The contents are heated gradually. The liquid begins to boil after some time. The vapour begins to rise up and passes down the side arm into the condenser. The temperature rises rapidly and reaches a constant value. The temperature of the distillate is noted down, which is equal to the boiling point of the liquid.

The vapour is condensed and collected into the receiver. The flame is adjusted so that the distillate is collected at the rate of one to two drops per second. Distillation should be continued until a small volume of liquid remains in the flask.

Large Scale Equipment for Simple Distillation

Construction : A simple still as shown in Figure 7-6 is used for large-scale distillation. It is made up of stainless steel, copper or any other suitable material. A still of this kind has a limited heating surface and functions perfectly with volatile solvents, but is not useful for concentrating dilute solutions. Specially designed stills suited to one product or a group of products are used for frequent and continuous use.

A thermometer is fixed to the still to note the temperature of the boiling liquid. An observation window (sight glass) in the hood is helpful to the operator to see the progress of the distillation and the level of the contents to be distilled. The still is connected to a condenser and then to a receiver. The still is heated using steam. Therefore, a steam inlet at the bottom of the still and an outlet for removing the condensed steam are provided.

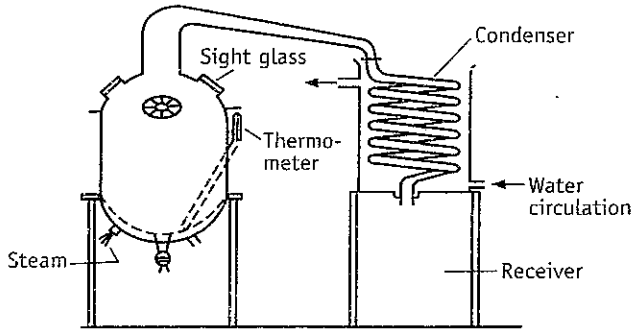


Figure 7-6. Equipment for simple distillation on large scale operation.

Working : A liquid to be distilled is filled into the still to one-half to two-third of its volume. Bumping is avoided by adding small pieces of porcelain or porous pot before distillation. A thermometer is inserted into the still. Water is circulated through the jacket of the condenser as shown in Figure 7-6.

Steam is passed through the inlet. The contents are heated gradually. The liquid begins to boil after some time. The vapour begins to rise up and passes into the condenser. The temperature rises rapidly and reaches a constant value. The temperature is noted down, which is equal to the boiling point of the liquid.

The vapour is condensed and collected into the receiver. The passage of steam is regulated so that the distillate is collected at a slower rate (a few

drops per second). Distillation should be continued until a small volume of liquid remains in the still.

Water stills are used for producing distilled water including water for injection on a continuous basis.

Preparation of Purified Water (BP) and Water for Injection (BP) By Distillation

The principle involved in the preparation of water for injection by distillation is same as that of the simple distillation. However, it is a special case for the following reasons.

(1) Gases dissolved in the raw water must be removed. These should not be allowed to contaminate the distillate. Such gases include carbon dioxide. Ammonia is the most important gas to be avoided.

(2) The carryover of soluble materials in the droplets must be avoided, particularly if the product is required for use as water for injection.

(3) Entrapment of liquid droplets by the vapour must be prevented. For this purpose, baffles are included in the path of the vapour between boiler and condenser.

(4) Contamination of the distillate by pyrogen from feed water must be avoided.

(5) The residue of solids must not be concentrated to a point where hydrolysis occurs. Otherwise, the distillate may be contaminated by volatile material produced during hydrolysis. For example, hydrolysis of chlorides produces hydrochloric acid.

Construction : The arrangement of an apparatus for the continuous production of distilled water or water for injection is shown in Figure 7-7. The distillation apparatus consists of a boiler, which may be made of cast iron. Baffles and condenser tubes are made up of stainless steel or monel metal. The top of the condenser jacket is open, so that gases from water can escape into atmosphere. The condenser tubes are vertical and open at both ends, as shown in Figure 7-7.

Working : Water (feed) enters at the base of the still and rises in the jacket, which contains a number of tubes. In the condenser tubes, the condensed liquid descends. The rising feed water gets heated on account of condensate in the tubes. The rate of flow is adjusted in such a way that the water gets heated to 90–95 °C, before it enters the boiler. The dissolved gases in water escape to the atmosphere. The heated water then enters the boiler, in which steam is circulated under pressure through a copper coil. The steam that is obtained by feed water cannot escape except through the condenser tubes, whose upper ends are protruded into the boiler head. The

descending steam is condensed into distilled water, which flows from the lower ends of the tubes.

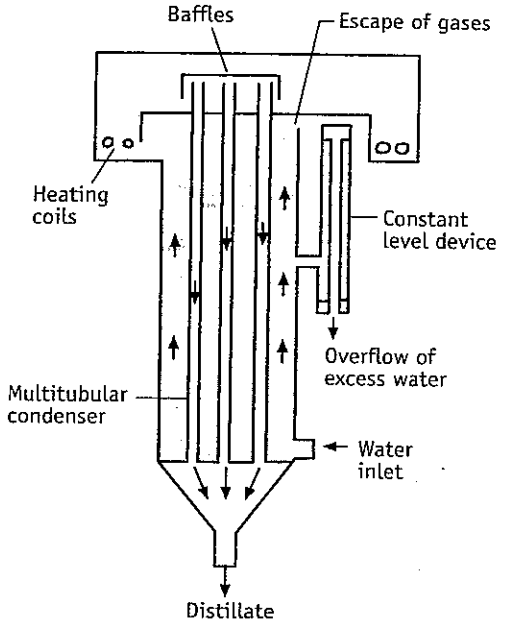


Figure 7-7. Construction of a distillation unit for the preparation of water for injection.

Advantages : This process is economical as the amount of steam used in coils is reduced on account of preheating of feed water by counter-current flow of the condensate. This also facilitates the escape of dissolved gases without any additional effort.

Comment 7-4. What are the precautions taken while assembling the apparatus for simple distillation?

FLASH DISTILLATION

Flash distillation is defined as a process in which the entire liquid mixture is suddenly vaporized (flash) by passing the feed from a high pressure zone to a low pressure zone.

Flash distillation is also known as *equilibrium distillation*, i.e. separation is attempted when the liquid and vapour phases are in equilibrium. This method is frequently carried out as a continuous process and does not involve rectification.

Principle : When a hot liquid mixture is allowed to enter from a high-pressure zone into a low-pressure zone, the entire liquid mixture is

suddenly vaporised. This process is known as *flash vaporisation*. During this process the chamber gets cooled. The individual vapour phase molecules of high boiling fraction get condensed, while low boiling fraction remains as vapour. This process requires certain amount of time. Therefore, the liquid and vapour are kept in intimate contact until equilibrium is achieved. The liquid fraction is collected separately. The vapour is separated from the liquid and further allowed to condense.

Uses : Flash distillation is used for separating components, which boil at widely different temperatures. It is widely used in petroleum industry for refining crude oil.

Advantages : Flash distillation is a continuous process. It is used for obtaining multi-component systems of narrow boiling range, especially in oil refinery. Examples are petroleum ether 60, 80, etc.

Disadvantages : Flash distillation is not effective in separating components of comparable volatility. It is not suitable for two component systems. It is not an efficient distillation when nearly pure components are required, because the condensed vapour and residual liquid are far from pure.

Equipment

Construction : The construction of a flash distillation apparatus is shown in Figure 7-8. It consists of a pump, which is connected to a feed reservoir. Pump helps in pumping the feed into the heating chamber which contains a suitable heating mechanism. The other end of the pipe is directly introduced into the vapour-liquid separator through a reducing valve. The vapour outlet is provided at the top of the separator and liquid outlet is provided at the bottom.

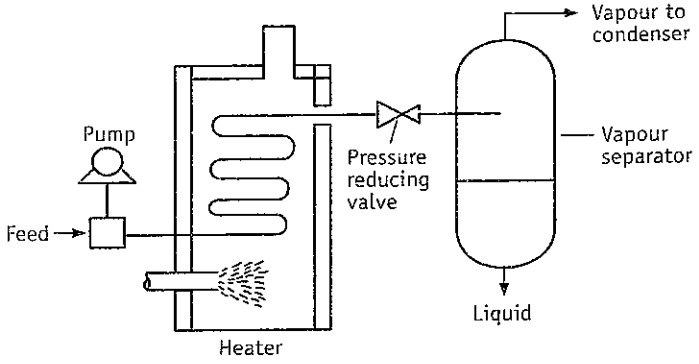


Figure 7-8. Apparatus for flash distillation.

Working : The feed is pumped through a heater at a certain pressure. The liquid gets heated, which enters the vapour-liquid separator through a pressure-reducing valve. Due to the drop in pressure, the hot liquid flashes,

which further enhances the vaporisation process. The sudden vaporisation induces cooling. The individual vapour phase molecules of high boiling point fraction get condensed, while low boiling point fraction remains as vapour. The mixture is allowed for a sufficient time, so that vapour and liquid portions separate and achieve equilibrium. The vapour is separated through a pipe from above and liquid is collected from the bottom of the separator.

By continuously feeding into the still, it is possible to obtain continuous flash distillation. The operating conditions can be adjusted in such a way that the amount of feed exactly equals the amount of material removed. Therefore, vapour and liquid concentrations at any point remain constant in the unit.

FRACTIONAL DISTILLATION

Fractional distillation is a process in which vaporisation of liquid mixture gives rise to a mixture of constituents from which the desired one is separated in pure form.

This method is also known as *rectification*, because a part of the vapour is condensed and returned as a liquid. This method is used to separate miscible volatile liquids, whose boiling points are close, by means of a fractionating column.

Fractional distillation is different from simple distillation. In simple distillation, vapour is directly passed through the condenser. In fractional distillation the vapour must pass through a fractionating column in which partial condensation of vapour is allowed to occur. In simple distillation, condensate is collected directly into the receiver, while in fractional distillation, condensation takes place in the fractionating column, so that a part of the condensing vapour returns to the still.

Principle : From the operational point of view, fractional distillation is a mass transfer process involving counter-current diffusion of the components at each equilibrium stage.

When a liquid mixture is distilled, the partial condensation of the vapour is allowed to occur in a fractionating column. In the column, ascending vapour from the still is allowed to come in contact with the condensing vapour returning to the still. This results in enrichment of the vapour with the more volatile component. By condensing the vapour and reheating the liquid repeatedly, equilibrium between liquid and vapour is set up at each stage, which ultimately results in the separation of a more volatile component.

Applications : Fractional distillation is used for the separation of miscible liquids such as acetone and water, chloroform and benzene.

Disadvantage : Fractional distillation cannot be used to separate miscible liquids, which form azeotropic mixtures.

Theory : According to the principles of colligative properties, when a substance is dissolved in a liquid, the vapour pressure of solvent is lowered. When two miscible liquids are mixed, each may be considered as a solution of one in the other. The vapour pressure of each component is lowered. The pressure exerted by each one is known as *partial pressure*.

According to *Dalton's law*, the total pressure exerted by a gaseous mixture is the sum of the individual partial pressures of the component gases. If A and B are two miscible liquids and, p_A and p_B represent their partial pressures, respectively, then Dalton's law may be mathematically expressed as:

$$\text{Total pressure} = p_A + p_B$$

Like other gas laws, Dalton's law holds strictly good only when the partial pressures are not too high. Dalton's law is important because it permits the estimation of total vapour pressure, which should be equal to atmospheric pressure so as to reach the boiling point. At boiling point, the vaporization is maximum.

Based on the boiling point behaviour, the binary mixtures are classified into three classes.

Boiling Point–Composition Curves of Mixtures

Since repeated vaporisation and condensation processes are involved simultaneously, the composition of liquid and vapour phases change continuously. Hence, boiling point-composition curves are helpful in predicting whether the separation is possible or not, if possible, whether it is easy or difficult. These are helpful in designing the equipment for fractional distillation.

Boiling point–composition curves are constructed as follows:

(1) Mixtures of liquid A and liquid B are prepared in different proportions.
(2) Boiling point of each mixture is determined.
(3) Liquid composition of each component is analysed at its boiling point.
(4) Vapour composition of each component is analysed at its boiling point.
(5) The boiling points are plotted on y-axis against composition of the mixture (x-axis). The resulting plot is shown in Figure 7-9.
(6) The upper curve represents the vapour phase composition.
(7) The lower curve represents the liquid phase composition.

(8) The different areas correspond to the existence of liquid, vapour and liquid plus vapour phases.

The curves represent the equilibrium condition. Therefore, they are helpful in drawing conclusions regarding the composition of components at any given temperature.

Fractional Distillation–Type I Miscible Liquids (for Ideal Solutions)

Fractional distillation is suitable for a system when the boiling point of the mixture is always intermediate between those of pure components. There is neither a maximum nor a minimum in the composition curves as shown in Figure 7-9. These systems are known as *zeotropic mixtures*. E.g. include benzene and toluene, carbon tetrachloride and cyclohexane, and water and methanol.

The usefulness of Figure 7-9 in the design of fractional distillation is illustrated in Figure 7-14.

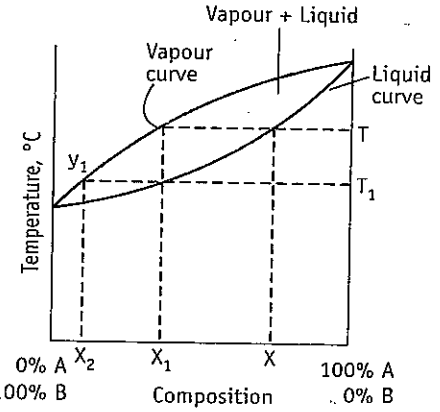


Figure 7-9. Boiling point–composition diagram of miscible liquids.

Fractional Distillation–Azeotropic Mixtures

Many liquid mixtures cannot be separated completely into pure components by simple distillation, because the volatilities of the components are equal. Such a mixture is known as an azeotrope (*Greek*: boil unchanged).

Azeotropic solution is a solution which distils unchanged at a constant temperature.

Such solutions are also known as *constant boiling mixtures*. An example of this type is 89.43 mol % mixture of ethanol and water at atmospheric pressure. This mixture has a relative volatility of 1.0, further purification cannot be obtained by conventional distillation. These solutions deviate from the Raoult's law to a large extent.

Minimum boiling point azeotropic solutions–Type II solutions (non-ideal solutions) : System that exhibits a minimum value in the boiling point-composition curve is shown in Figure 7-10. Such a system is known as *azeotropic mixture* with a maximum vapour pressure or minimum boiling point. Examples include chloroform and acetone, pyridine and acetic acid, and water and nitric acid.

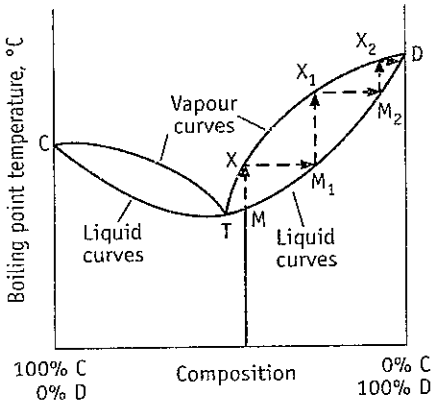


Figure 7-10. Boiling point-composition curves of a constant boiling azeotropic mixture having minimum boiling point.

The azeotropic mixture has a lower boiling point than that of the component with the least boiling point. At the minimum boiling point temperature, the liquid composition remains constant and is equal to the vapour composition (arising from such a liquid system). This is indicated by the point T, at the trough (Figure 7-10).

All mixtures of compositions lying between C and T (trough) can be separated by continuous fractional distillation. In this process, pure liquid C is recovered from the still and a mixture with constant composition (as of T) is obtained as a distillate from the condenser. In a similar way, all mixtures of compositions lying between T and D can be separated by continuous fractional distillation. In this process, pure liquid D is recovered from the still and mixture with constant composition (as of T) as condensate.

Since vapour gives constant composition of mixture, liquid curve (i.e. liquid present in the still) should be considered for the analysis (Figure 7-10).

Consider a hypothetical case (Figure 7-10) in which the mixture contains more of D than C, which is represented by M. If the mixture is distilled, the vapour has a composition of x. When this vapour is condensed, the liquid composition is represented by M_1, which is richer in D than C. When this liquid is redistilled, the vapour has composition of x_1. When this vapour is condensed, the liquid has the composition of M_2. Thus on repeated distillation (fractional distillation), the liquid D will be in pure

form and remains in still. Similar arguments can be proposed for fractional distillation of component C by considering left-side curves to T (trough).

Maximum boiling point azeotropic solutions–Type III solutions (non-ideal solutions) : System that exhibits a maximum value in the boiling point-composition diagram is shown in Figure 17-11. Such a system is known as *azeotropic mixture* with a minimum vapour pressure or maximum boiling point. Examples include benzene and ethanol, water and ethanol.

The azeotropic mixture has a higher boiling point than that of the component with the higher boiling point. At the maximum boiling point temperature, the liquid composition remains constant and is equal to the vapour composition (arising from such a liquid system). This is indicated by coincidence at the peak, P (Figure 7-11).

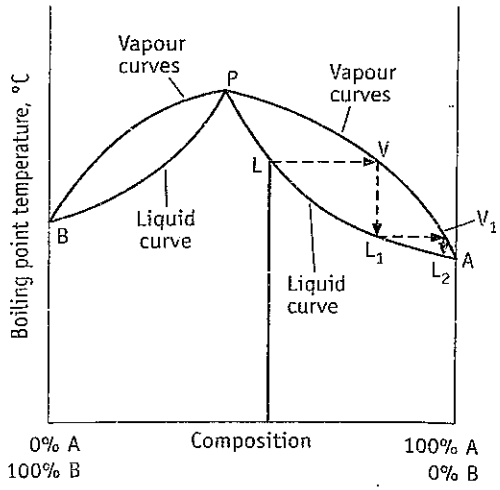


Figure 7-11. Boiling point-composition curves of a constant boiling azeotropic mixture having maximum boiling point.

All mixtures of compositions lying between P (peak) and A give pure liquid A as distillate and a mixture of A and B with constant composition in the still. In a similar way, all mixtures of compositions lying between B and P give pure B as distillate and a mixture of A and B with constant composition in the still.

Consider a hypothetical case (Figure 7-11) in which the mixture contains more of A than B, which is represented by L. If this mixture is distilled, the composition of vapour v is richer in A and poorer in B. At this state, the liquid residue in the distillation flask will be richer in B and poorer in A. The vapour at v is condensed, the liquid composition is represented by L_1. If this liquid is distilled, the composition of vapour v_1 is further rich-

er in A and poorer in B. Thus on repeated distillations (i.e. fractional distillation), the liquid A in pure form can be obtained as a distillate. But the residue remained in the still is always the mixture of A and B of constant composition. Similar arguments can be proposed for fractional distillation of component B by considering left-side curves to P.

General Method for Fractional Distillation

Construction : The assembly of apparatus for fractional distillation on a laboratory scale is shown in Figure 7-12. On a large scale, the construction of equipment for fractional distillation is shown in Figure 7-13. The fractionating column is inserted between the still and the condenser. A provision is made for the supply of heat (usually a steam coil) at the bottom of the column. At the top of column, a condenser is provided. The column has a large area for providing sufficient flow conditions. The broken lines across the column represent the contacting devices.

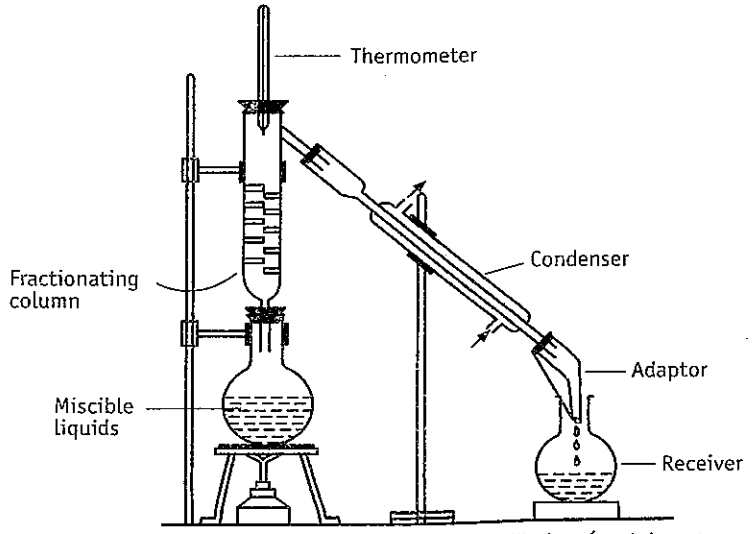


Figure 7-12. Assembly of apparatus for fractional distillation (on laboratory scale).

Working : The mixture to be distilled is fed to the boiler and heated usually by steam. The sequence of events occurring in the fractionating column can be illustrated using the following general example (Figure 7-13).

Consider a mixture of two miscible liquids A and B containing 20 % of A and 80 % B. Liquid A (More Volatile Component, MVC) is having a lower boiling point than B (Less Volatile Component, LVC). These liquids do not produce constant boiling point mixture. The boiling point composition curves of this mixture are shown in Figure 7-14, which is similar to Figure 7-9, but written several times so as to represent the steps (i.e. in fractions) in fractional distillation.

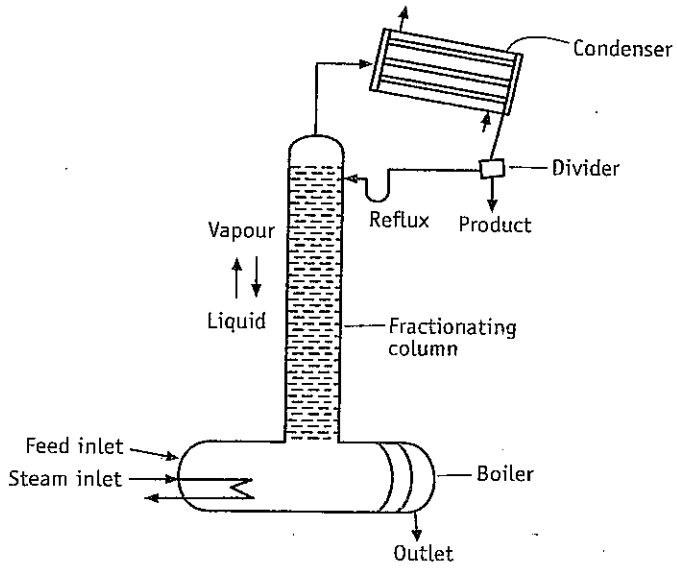


Figure 7-13. Fractional distillation apparatus for large scale operation.

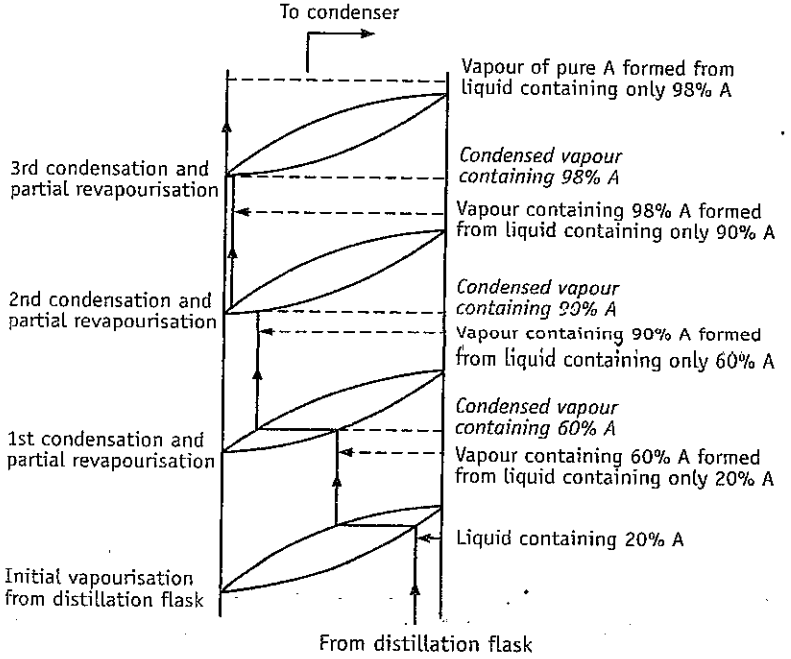


Figure 7-14. Sequence of boiling point–composition diagrams to illustrate the fractional distillation of a mixture of components.

(1) When the boiling point of the mixture is reached, the vapour-composition curves are drawn as shown by lowest pair of curves (Figure 7-14). These curves indicate that the vapour contains 60 % of A.

(2) When this vapour is condensed, the resulting liquid is again heated to boiling point, this vapour gives the composition containing 90 % of A (second pair of curves from the bottom).

(3) This vapour impinging on a cool surface and gets condensed. This fraction is revaporised by heating to its boiling point. This boiling point curve of this distillate indicates 98 % of A (Third pair of curves from the bottom).

(4) This fraction of vapour impinges on a cooling surface. This gives fourth pair of curves. Now this vapour contains higher (more than 98 %) proportion of A, i.e. vapour of pure component.

(5) The vapour moves to a condenser at the top of the column and gets condensed.

Thus, repetition of these processes yield pure A as shown in the curves in Figure 7-14. The proportion of B in the ascending vapour becomes progressively smaller and entirely eliminated at its upper most point. The liquid B trickles downward to the distillation flask being further freed from liquid A on its downward journey.

Once distillation is commenced, the size of the flame is adjusted so that liquid passes over at a rate of one drop per every two or three seconds. Once the low boiling point fraction has passed over, distillation should be stopped. The liquid available in the still is pure B. It can be collected as such or purified further by simple distillation (keeping the fractionating column assembly).

The above process forms the basis of the continuous method of fractional distillation. Distillation is continued until all the MVC has been distilled off from the top as the product and the LVC is left in the still as a separate product.

Efficiency of the Fractional Distillation

The efficiency of separation of a mixture may be expressed in several ways.

Length of the fractionating column : A state of dynamic equilibrium is required for the separation. A maximum degree of separation of the components is obtained along the length of the column.

Reflux ratio : *Reflux ratio* is the quotient of the amount of liquid returning through the column to the amount collected into the receiver during the same interval of time. A column operating under total reflux will not yield distillate. The reflux ratio should be high. It is controlled by means of a suitable still.

Heat input : Heat input to the still should be controlled. If it is too little, the packing is insufficiently wetted. If it is too high, velocity may be too great for equilibrium to be attained. The size of the flame should be adjusted so that liquid passes over at a rate of one drop for every two or three seconds.

Column temperature : For a column operating at a temperature above 60 °C, heat loss should be prevented by insulation. Examples are asbestos cord and silver vacuum jacket. For temperature above 100 °C, the column is surrounded by a heating jacket, which is generally adjusted to the temperature of the vapour that emerges from the top of the column. Heat loss will cause excessive condensation within the column, which may result in flooding. It will also disturb the steady state temperature gradient along the column.

Other experimental conditions necessary for good separation are:

(1) There should be a comparatively large amount of liquid continuously returning through the column.

(2) Thorough mixing of liquid and vapour.

(3) A large active surface of contact between liquid and vapour.

Fractionating Columns

Generally, it is necessary to conduct distillation several times by appropriate means in order to separate a mixture of miscible liquids. This can be avoided by employing fractionating column for a reasonably complete separation. In fractional distillation, special type of still-heads are required so that condensation and revaporisation are affected continuously. These are known as *fractionating columns.*

A fractionating column is essentially a long vertical tube in which the vapour passes upward and gets partially condensed. The condensate flows down the column and is returned eventually to the flask. The columns are constructed so as to offer the following advantages simultaneously.

(1) It offers a large cooling surface for the vapour to condense.

(2) An obstruction to the ascending vapour allows easy condensation. The obstruction also retards the downward flow of liquid, which is a high boiling component.

Fractionating columns can be divided into two groups.

Packed columns : In this type, some form of packing is used in the column to affect the necessary liquid/vapour contact. The packing may consist of single turn helices (spirals) of wire or glass, glass rings, cylindrical glass beads, stainless steel rings etc. The height of packing is equivalent to *one theoretical plate.* A few types of fractionating columns are shown in Figure 7-15.

Construction : Packed column consists of a tower containing a packing that becomes wetted with a film of liquid, which is brought into contact with the vapour in the intervening spaces.

The same type of fractionating columns can be obtained in various lengths.

(a) A long fractionating column is necessary when the boiling points of the constituents are lying fairly close together.

(b) A short fractionating column is necessary when the boiling points of the constituents differ considerably.

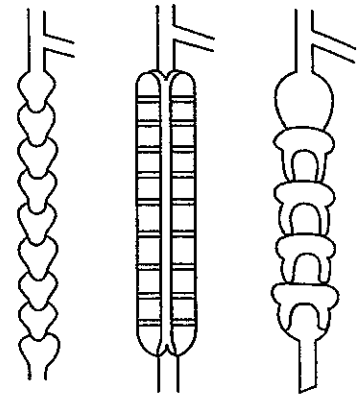


Figure 7-15. Different types of fractionating columns.

Applications : Packing must be uniform so as to obtain proper channels. If packing is irregular, mass transfer becomes less effective. Packed columns are mainly used in laboratories. Example is Widmer column. (Figure 7-16).

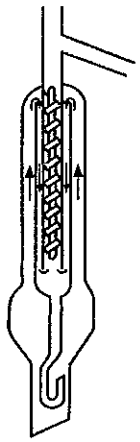


Figure 7-16. Widmer column.

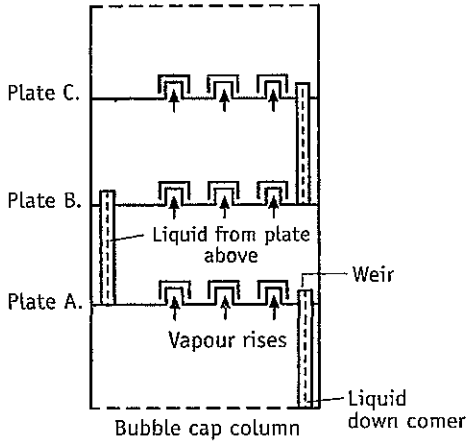


Figure 7-17. Construction of bubble cap column for fractional distillation.

Plate columns : Many forms of plates are used in the fractionating columns. These can be divided into two types, which are commonly used in pharmacy.

(a) Bubble-cap plates (b) Turbo grid plates

Bubble cap column is used in large distillation equipment (Figure 7-17).

Construction : The column consists of a number of plates mounted one above the other (Figure 7-17). The plates have a weir leading to a downcomer. Caps are present on each plate, which allow the vapour to escape by bubbling through the liquid.

Working : Ascending vapour from the still passes through the bubble-caps on plate A and the rising vapour will be richer in the more volatile component. This vapour passes through the liquid on plate B and partially condensed. The heat of condensation partially vaporizes the liquid. The process of condensation and vaporisation will be repeated at plate C and so on all the way up the column. Each bubble-cap plate has the same effect as a separate still.

Advantages : The bubble cap plate is effective over a wide range of vapour-liquid proportions and velocities. There is an excellent contact as the vapour bubbles through the liquid.

Disadvantages : (1) A layer of liquid on each plate results in considerable hold-up of liquid over the entire column.

(2) The need to force the vapour out of the caps through the liquid leads to a large pressure drop through the column.

(3) The column does not drain even after completion of distillation.

(4) The structure is complicated making construction and maintenance expensive.

AZEOTROPIC AND EXTRACTIVE DISTILLATION

Azeotropic solutions (or constant boiling solutions) cannot be completely separated by fractional distillation, because either the vapour or the liquid in the still has a mixture of components. The principle of azeotropic distillation and extractive distillation lies in the addition of a new substance to the mixture so as to increase the relative volatility of one of the two key components and thus making separation relatively easy. Azeotropic ternary mixtures with minimum boiling point (or maximum vapour pressure) are pharmaceutically important.

Azeotropic distillation is a distillation method in which azeotropic mixture is broken by the addition of a third substance, which forms a new azeotrope with one of the components.

The relative volatility of the liquid mixture can be changed by adding a third substance. For example, benzene is added to the azeotropic mixture of water and ethyl alcohol. Benzene breaks the mixture of water-ethyl alcohol and forms a new azeotrope between benzene and ethyl alcohol. The volatility of the water (more polar liquid) is enhanced. On distillation,

water distills at 65.85 °C leaving alcohol and benzene behind. The boiling point of this binary mixture is 68.2 °C and benzene gets distilled leaving pure alcohol behind. It can be distilled off at 78.3 °C. The benzene can be recycled. Thus, using fractional distillation method, absolute alcohol can be prepared.

When glycerin is added to the above mixture, the vapour pressure of water is lowered. Practically pure ethanol can be obtained from the fractionating tower.

In *extractive distillation*, the third substance added to the azeotropic mixture is relatively nonvolatile liquid compared to the components to be separated.

The third component is withdrawn at the base of the fractionating column.

Example is separation of toluene from paraffin hydrocarbons of approximately same molecular weights. The separation of toluene and iso-octane (example for hydrocarbon) is difficult. In the presence of phenol, the relative volatility of iso-octane increases, therefore, separation of toluene is relatively easy. In another example, furfural is added for the separation of butadiene from its mixture containing butane and butene.

Applications : The liquor from fermentation process is a common source of ethanol and contains approximately 8 to 10 %. Absolute alcohol can be prepared by azeotropic distillation. Petroleum refineries and distilleries use these types of distillation.

Comment 7-5. Azeotropic distillation is used to separate individual components into pure state. True or false. Explain.

DISTILLATION UNDER REDUCED PRESSURE

Distillation under reduced pressure may be defined as a distillation process in which the liquid is distilled at a temperature lower than its boiling point by the application of vacuum.

Vacuum pumps and suction pumps are used to reduce the pressure on the liquid surface. Distillation under reduced pressure is based on the principle of simple distillation with some modifications.

Principle : Liquid boils when vapour pressure is equal to the atmospheric pressure, i.e. pressure on its surface. If the external pressure is reduced by applying vacuum, the boiling point of liquid decreases. Therefore, the liquid boils at a lower temperature. This principle is illustrated using an example of water. Water boils at 100 °C at an atmospheric pressure of 101.31 kPa (760 mmHg). At 40 °C, the vapour pressure of water is approximately 9.33 kPa (70 mmHg). Hence, the external pressure is

reduced to 9.33 kPa (70 mmHg) where water boils at 40 °C. The net result is an increase in the rate of mass transfer into vapour.

The important factor in evaporation is:

$$\text{Mass of vapour formed, } \propto \frac{\text{vapour pressure of evaporating liquid}}{\text{external pressure}}$$

According to this formula, if water is allowed to evaporate at 40 °C and at 9.33 kPa (70 mmHg) pressure, the mass of vapour formed in unit time is approximately 11 times, i.e. ratio 760/70 for water.

Applications : Distillation under reduced pressure is essential and finds a number of applications.

Preventing degradation of active constituents : During extraction, concentration and processing at higher temperatures, the active constituents may undergo decomposition (inactivation). A few examples are given below. Hence extraction and concentration should be done at a lower temperature (≈55 °C) under reduced pressure.

Category	*Reaction*	*Examples*
Enzymes	Inactivation	malt extract, pancreatin
Vitamins	Oxidation	thiamine, ascorbic acid
Glycosides	Hydrolysis	anthraquinones
Alkaloids	Racemization	hyocyamine to atropine
Tannins	Precipitation	phlobatanins to phlobaphenes

Changing physical form : In the preparation of Cascara sagrada tablets, granular extract is suitable. Drying at the atmospheric pressure yields a dense, compact residue, which is not desirable. In the initial stage, the liquid extract is concentrated under atmospheric pressure or under partially reduced pressure, until the residue has the consistency of treacle. The pressure is then quickly reduced, where upon the treacly semi-solid swells up due to sudden evolution of water vapour. This produces a light porous mass, which can readily be passed through a sieve to form a granular powder.

Disadvantages : In vacuum distillation, persistent foaming occurs. This may be overcome by adding capryl alcohol to the liquid or by inserting a fine air capillary tube in the second neck of the Claisen flask. The stream of air is drawn in and breaks the rising foam. The above method is not suitable for the preparation of semisolid or solid extracts.

Small Scale Apparatus—Distillation Under Reduced Pressure

Assembling of apparatus : It consists of a double-neck distillation flask known as *Claisen flask* (Figure 7-18). Thick walled glass apparatus with interchangeable standard glass joints are used for vacuum distillation.

In one of the necks of the Claisen flask, a thermometer is fitted. The second neck prevents splashing of the violently agitated liquid. Bumping occurs readily during vacuum distillation. Placing a fine capillary tube in the second neck of the flask can prevent bumping. The capillary tube is dipped in the boiling liquid, so that a stream of air bubbles is drawn out. Water bath or oil bath is used for heating.

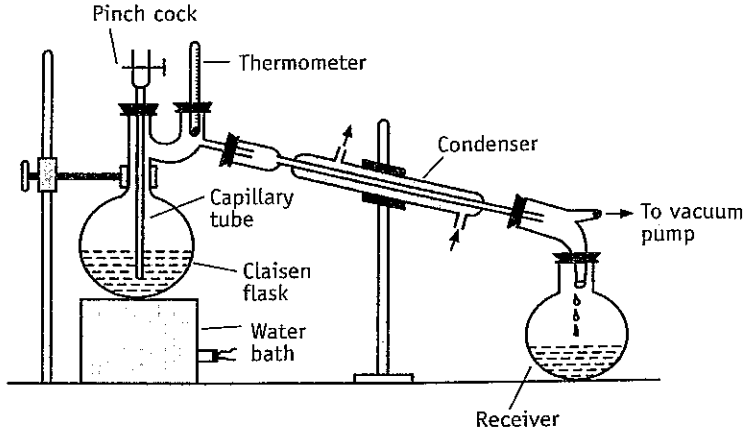


Figure 7-18. Assembly of apparatus for distillation under reduced pressure (on laboratory scale).

The Claisen flask is connected to a receiver through a condenser. Vacuum pump is attached through an adapter to the receiver. A small vacuum gauge (manometer) should be inserted between the pump and the receiver.

Procedure : The liquid to be distilled is filled one-half to two-third volume of the flask. Small pieces of porcelain are added to the liquid for facilitating distillation and prevent bumping. The capillary tube and thermometer are kept in place in the flask (Figure 7-18). The required vacuum is applied. The contents are heated gradually. The temperature rises and liquid gets vaporised rapidly due to vacuum. The vapour passes through the condenser. The condensate is collected in the receiver. The temperature is noted down, which would be less than the boiling point of the liquid.

When a large volume of a liquid is to be distilled under reduced pressure, it is more convenient to distil comparatively small volumes at a time.

Large Scale Apparatus Using Vacuum Stills for Distillation Under Reduced Pressure

Construction : The general construction of a large scale equipment for distillation under reduced pressure is shown in Figure 7-19. The vacuum jacketed still is generally made of stainless steel, copper or any other material, which can withstand a high vacuum. An observation window in

the hood is helpful to see the progress of the distillation and also the level of the liquid contents. The still is fitted with a drainpipe at the bottom and an air vent. The still is connected to a condenser. A thermometer is incorporated in the still. Vacuum pump through vacuum gauge is connected as shown in Figure 7-19.

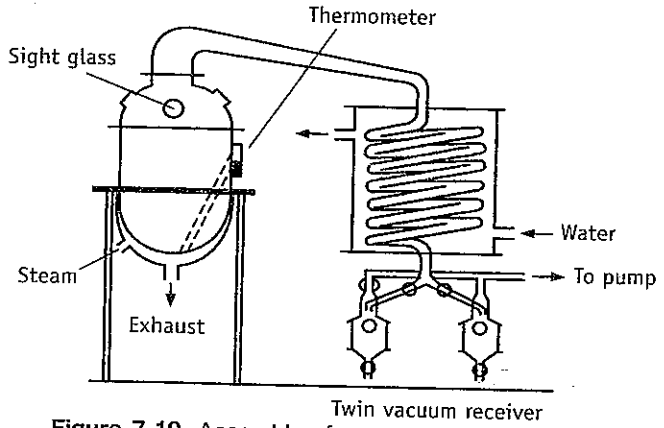


Figure 7-19. Assembly of apparatus for distillation under reduced pressure (on industrial scale).

Working : The still is filled with the liquid to be distilled through an attachment of a pipe with a tap. The other end of the pipe is connected to a reservoir of liquid, so that it can be filled at a controlled flow rate. Vacuum is created by means of a vacuum pump. Using the steam, the liquid is gradually heated. The temperature rises and the liquid gets vaporised rapidly due to vacuum. The vapour passes through the condenser and the condensate is collected into a receiver.

Normally two receivers are fitted with suitable arrangement of cocks, so that they can be used alternatively, the distillate being collected from one, while the other is connected to the still under vacuum. Therefore distillation need not be stopped.

Distillation is stopped while the contents of the flask are sufficiently fluid to run off through the drain pipe at the bottom. When spongy powdery mass is desired, the still can be provided with a stirring arrangement, which also hastens vaporization. According to the requirements, the capacity may be a few litres to thousands of litres.

Comment 7-6. Should the distillation be carried out at atmospheric pressure or can it be carried out at altered pressure?

Comment 7-7. Suggest the methods to avoid foaming during vacuum distillation?

Comment 7-8. Vacuum distillation is suitable for the purification of vitamins. True or false. Explain.

STEAM DISTILLATION

Steam distillation is a method of distillation carried with the aid of steam and is used for the separation of high-boiling substances from non-volatile impurities.

High-boiling liquids cannot be purified by simple distillation, since the constituents in the mixture tend to decompose at higher temperatures. In such cases, steam distillation is employed. Steam distillation is used for the separation of immiscible liquids.

For substances, which are insoluble in water and not decomposed by heat, steam distillation provides an alternative to distillation under reduced pressure. Steam distillation is the most common example of *differential distillation*.

Principle : A mixture of immiscible liquids begins to boil when the sum of their vapour pressures is equal to the atmospheric pressure. In case of a mixture of water and turpentine, mixture boils below the boiling point of pure water, though the turpentine boils at a much higher temperature than that of water.

For example, the boiling point of turpentine is about 160 °C. But when it is mixed with water and heated, the mixture boils at about 95.6 °C. At this temperature, the vapour pressure of water is 86.245 kPa (647 mmHg) and that of turpentine is 15.06 kPa (113 mmHg). The sum of the vapour pressures is 101.31 kPa (760 mmHg) which is normal atmospheric pressure. Thus, high boiling substances may be distilled at a temperature much below its boiling point, when water (steam) is used.

For volatile substances, which are miscible with water, steam distillation involves the same principle as fractional distillation.

Applications : (1) Steam distillation is used for the separation of immiscible liquids. E.g. toluene and water.

(2) This method is used for extracting most of the volatile oils such as clove, anise and eucalyptus.

(3) It is useful in purification of liquid with high boiling point, e.g. essential oil of almond.

(4) Camphor is distilled by this method.

(5) Aromatic waters are prepared by this method.

Advantages : Volatile oils can be separated at a lower temperature in steam distillation, without any decomposition and loss of aroma. If a substance has low volatility, it can be satisfactorily distilled, provided its molecular weight is considerably higher than water.

Disadvantages : Steam distillation is not suitable when immiscible liquid and water react with each other.

Apparatus Used for Laboratory Scale

Assembly of apparatus : The assembly of apparatus for steam distillation on laboratory scale is shown in Figure 7-20. It consists of a metallic '*steam can*' fitted with a cork having two holes. Through one of the holes, a long tube is passed so as to reach almost the bottom of the steam generator. This tube acts as a safety tube, so that in case the pressure inside the steam generator becomes too much, water will be forced out of it and the pressure will be relieved. Moreover, when steam starts coming out from the safety tube, it indicates that the steam can is almost empty. Through another hole, a bent tube is passed. The other end of the bent tube is connected to the flask containing non-aqueous liquid (for example, crude containing volatile oil) through a rubber bung. This tube should reach almost the bottom of the flask.

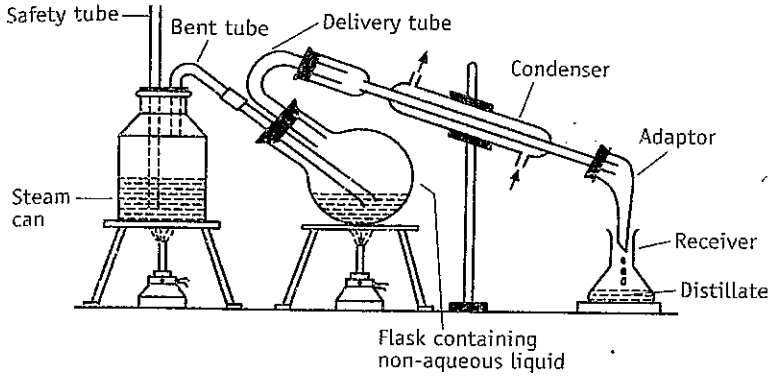


Figure 7-20. Assembly of apparatus for steam distillation (on laboratory scale).

Through the other hole of the rubber bung, a delivery tube is inserted which connects the flask and the condenser. The condenser is connected to a receiver flask using an adaptor. Provisions are made to heat the *steam* can and flask.

Procedure : The non-aqueous liquid is placed in the flask. A small quantity of water is added to it. *Steam can* is filled with water. The steam generator and the flask are heated simultaneously, so that a uniform flow of steam passes through the boiling mixture. The mixture gets heated. The steam carries the volatile oil and passes into the condenser, which is cooled by cold water. The condensed immiscible liquid is collected into the receiver.

Distillation is continued until all the non-aqueous liquid has been distilled. In the receiver, water and organic liquid form two separate layers, which can be easily separated using a separating flask.

For volatile substances, which are miscible with water, distillation with steam would involve the same principle of fractional distillation.

Equipment Used on Industrial Scale

Construction : Steam distillation unit is diagrammatically shown in Figure 7-21. It consists of a jacketed still with a perforated plate which forms a false bottom. Manholes are provided at the top and side for charging and discharging. A Florentine receiver is placed between the still and condenser. The condenser is cooled by circulating cold water.

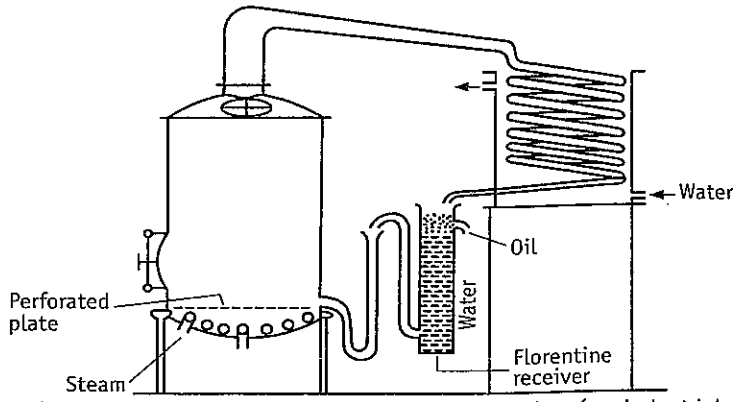


Figure 7-21. Assembly of apparatus for steam distillation (on industrial scale).

Working : The material from which the volatile oil has to be extracted is placed in the still above the perforated plate. Steam is admitted to the jacket of the still. The water and material present in the still are heated to boiling. Simultaneously steam is also injected below the materials through a steam pipe from the jacket. The steam carries the volatile oil and gets condensed in the condenser, which is cooled by cold water. The condensate is collected into the Florentine receiver. Most volatile oils are lighter than water and well separated from the distillate as an upper layer and removed from the upper spout. The water can run off from the spout on the left and returns to the still.

Some volatile oils are heavier than water in which case the separation is reversed. Oil is collected from the lower spout.

Variants : (1) For volatile substances, which are miscible with water, distillation method combines the principles of the steam and fractional distillations.

(2) If the specific gravity of the oil is near 1.0, then separation does not take place. In such cases, it may be necessary to collect the whole of the distillate. Further it is extracted with an (volatile) organic solvent. The solvent should be distilled off to get the volatile oil.

Comment 7-9. For a substance having high molecular weight and low volatility, steam distillation is a better separation technique. True or false, Justify.

MOLECULAR DISTILLATION

Molecular distillation is defined as a distillation process in which each molecule in the vapour phase travels mean free path and gets condensed individually without intermolecular collisions on application of vacuum.

Molecular distillation is based on the principle of the simple distillation with some modifications. This is also called *evaporative distillation or short path distillation.*

Principle : The substances to be distilled in molecular distillation have very low vapour pressures. Examples are viscous liquids, oils, greases, waxy materials and high molecular weight substances. These boil at very high temperatures. In order to decrease the boiling point of the liquids, high vacuum must be applied.

The vapour pressure above the liquid is much lower than that of the saturated vapour in equilibrium. At very low pressure, the distance between the evaporating surface and the condenser is approximately equal to the mean free path of the vapour molecules. Molecules leaving the surface of the liquid are more likely hit the condenser surface than to collide with other molecules. Little or no re-condensation takes place at the surface of the liquid.

Applications : Molecular distillation is used for the purification and separation of chemicals of low vapour pressure.

(1) Purification of chemicals such as tricresyl phosphate, dibutyl phthalate and dimethyl phthalate.
(2) More frequently used in the refining of fixed oils.
(3) Vitamin A is separated from fish liver oil. Vitamin E is concentrated by this method from fish liver oils and other vegetable oils.
(4) Free fatty acids are distilled at 100 °C. Steroids can be obtained between 100 °C and 200 °C, while triglycerides can be obtained from 200 °C onwards. Proteins and gums will remain as non-volatile residues. Thus, the above mixture can be separated by molecular distillation.

Theory : The *mean free path of a molecule* is defined as the average distance through which a molecule can move without coming into collision with another.

The mean path (λ) can be expressed mathematically as:

$$\lambda = \eta\sqrt{\frac{3}{p\rho}} \qquad \ldots(11)$$

where p = vapour pressure, kPa; ρ = density, kg/m^3
η = viscosity, Pa·s; λ = mean path length, m

For example, mean path (heavy molecules) of butyl phthalate is about 30 mm and of olive oil is 20 mm when measured at a pressure of 0.1 pascal.

The characteristics of the substance influence the method of distillation. According to equation (11):

(a) Liquids having low viscosity and density possess long mean path. Distillation is simple.

(b) Substances having high pressures possess low mean free path.

The mean free path can be increased by decreasing the viscosity (η), which can be obtained at high temperature and low pressure. Thus, non-volatile substances may become volatile and distillation is possible.

It is necessary to design the equipment based on the requirement of the molecular distillation. Some of them are as follows.

(1) The evaporating surface must be close to the condensing surface. This ensures the molecules to come in contact with the condenser as soon as they leave the evaporating surface. For this reason, this process is also known as *short path distillation*.

(2) The molecular collisions should be minimized because they change the direction of the path of molecules. In other words, intermolecular distances should be fairly high. It can be achieved under very high vacuum, usually of the order of 0.1 to 1.0 pascals.

(3) The liquid surface area must be as large as possible so that the vapour is evolved from the surface only, but not by boiling. Thus this process is also called *evaporative distillation*.

Based on the method of formation of the liquid film, apparatus may be divided into two types.

Falling Film Molecular Still or Wiped Film Molecular Still

Principle : In this method, vaporisation occurs from a film of liquid flowing down a heated surface under high vacuum. The vapour (molecules) travels a short distance and strikes the condenser nearby. Each molecule is condensed individually. The distillate is subsequently collected.

Construction : The construction of a wiped film molecular still is shown in Figure 7-22. The vessel has a diameter of one metre. The walls of the vessel are provided with suitable means of heating (jacket). Wipers are provided adjacent to the vessel wall. Wipers are connected to a rotating head through a rotor. The condensers are arranged very close to the wall (evaporating surface) as shown in Figure 7-22. Vacuum pump is connected to a large diameter pipe at the centre of the vessel. Provisions are made for collecting the distillate and the undistilled liquid residue at the bottom.

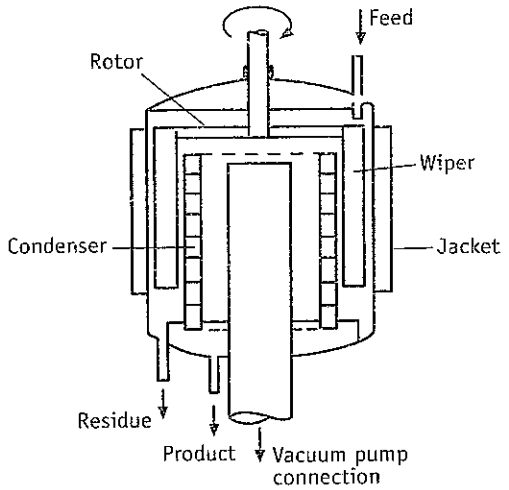


Figure 7-22. Wiped film molecular still.

Working : The vessel is heated by suitable means. Vacuum is applied at the centre of the vessel and wipers are allowed to rotate. The feed is entered through the inlet of the vessel. As the liquid flows down the walls, it is spread to form a film by PTFE (polytetrafluoroethylene) wipers, which are moving at a rate of 3 m/s. The velocity of the film is 1.5 m/s. Since the surface is already heated, the liquid film evaporates directly. The vapour (molecules) travels its mean free path and strikes the condenser. The condensate is collected into a vessel. The residue (undistilled or mean free path not travelled) is collected from the bottom of the vessel and re-circulated through the feed port for further distillation. Capacity is about 1000 L/h.

Centrifugal Molecular Still

Principle : In this method, liquid feed is introduced into a vessel, which is rotated at very high speed (centrifugal action). On account of heating, vaporisation occurs from a film of liquid on the sides of the vessel. The vapour (molecules) travels a short distance and gets condensed on the adjacent condenser. Each molecule is condensed individually. The distillate is subsequently collected.

Construction : The construction of a centrifugal molecular still is shown in Figure 7-23. It consists of a bucket-shaped vessel having a diameter of about 1 to 1.5 m. It is rotated at high speed using a motor. Radiant heaters are provided externally to heat the fluid in the bucket. Condensers are arranged very close to the evaporating surface. Vacuum pump is connected to the entire vessel at the top. Provisions are made for introducing the feed into the centre of the bucket, for receiving the product and residue for re-circulation.

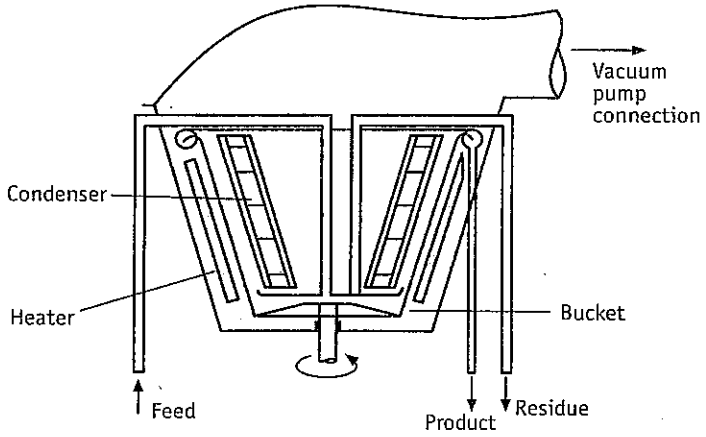


Figure 7-23. Centrifugal molecular still.

Working : Vacuum is applied at the centre of the vessel. The bucket shaped vessel is allowed to rotate at high speed. The feed is introduced from the centre of the vessel. Due to centrifugal action of the rotating bucket, liquid moves outward over the surface of the vessel and forms a film. Since, the radiant heaters heat the surface, the liquid evaporates directly from the film. The vapour (molecules) travels its mean free path and strikes the condenser. The condensate is collected into another vessel. The residue is collected from the bottom of the vessel and is re-circulated through the feed port for further distillation.

Disadvantages : Construction and operation are more complicated compared to falling film molecular still.

Comment 7-10. There is no relationship between mean free path and the assembly of apparatus for molecular distillation? True or false. Justify.

DESTRUCTIVE DISTILLATION

Destructive distillation is a distillation method in which the distillate is decomposition products of the constituents of the organic matter burnt in the absence of air.

This process is also known as *dry distillation*. It is not useful in laboratory practice, but one of the most important industrial processes for obtaining many valuable products from wood, coal, and animal matter. It involves the heating of dry organic matter in a suitable vessel in the absence of air, until all volatile substances are driven off. The distillate is the mixture decomposition products. Wood distillation industry and coal carbonisation industry provide many useful materials.

COMPRESSION DISTILLATION

Compression distillation method was developed to meet the needs of Navy and Army for fresh water, which is obtained from sea-water. The product obtained is quite pure and pyrogen-free. Therefore, it meets the requirements of the pharmaceutical industry. It is economical from the standpoint of consumption of fuel and water.

The feed water is heated in an evaporator for boiling. The vapour produced in the tubes is separated from entrained distilland in a separator. The vapour is then conveyed to a compressor, which compresses it and raises its temperature to about 118 °C. It then flows to the steam chest where it is condensed on the outer surface of the tube. During condensation, heat is released which is allowed for heating of the fresh feed in the tubes to the boiling point. The vapour is condensed and drained off as distillate.

Summary

Distillation is a separation of the components of a liquid mixture by a process involving vapourization and subsequent condensation at another place. The feed consists of a mixture of liquids and the products are separated as pure liquids. The distillation involves two steps: vapourization of liquids which requires the supply of heat and the condensation of the individual vapour molecules to become pure liquid which requires the removal of heat. Hence, two different heat exchangers are applied. The principles of vapourization of liquids can be understood from the theories of solutions, namely ideal solutions and real solutions. The theories of liquid-liquid solution such as Raoult's law and Dalton's law are applied for developing the distillation method in a simple manner. Volatility and relative volatility principles are used for predicting the separation of liquids. The assembly of distillation apparatus consists of distillation still-vapouring chamber, condenser and receiver. Thus simple distillation method is used for the preparation of distilled water and water for injection. Deviations from the Raoult's law are exhibited by a few liquid-liquid systems and hence the simple distillation is modified into a fractional distillation. In this method, the condenser is modified into a fractionating column in which equilibrium of vapour-liquid phases are obtained in several stages (times). In this process, one component becomes progressively purified and collected in a pure form. The other part remains as a liquid mixture (azeotropic liquids or constant boiling liquids). The phase diagrams of vapour-liquid (boiling point-composition curves) are useful. Based on the needs, different designs of fractionating columns are used and the efficiency of fractional distillation is evaluated. Another modification is the azeotropic distillation in which a new azeotropic solution is developed in order to obtain one of the liquids into a pure form. Thus several methods are developed which are having relative advantages in the separation.

Equilibrium distillation method is used for separation of liquid systems having narrow boiling range. In this method, the entire liquids (both components) are vapourzed at once (flash) and equilibrium is allowed to occur at a particular temperature, such that one part of liquid is condensed. Distillation under reduced pressure permits the vapourization of the liquid at the temperature lower than its boiling point. Simultaneously, the amount of vapour formed is 10 times higher under vacuum compared to normal atmospheric pressure. This method is used for the separation of thermosensitive products such as enzymes, vitamins, glycosides, alkaloids, tannins, etc. Steam distillation allows the easy vapourization of liquid, which are otherwise having high boiling points, with the aid of steam. For example, turpentine liquid is having high boiling point of 160 °C. When steam is mixed with the turpentine, the liquid-mixture boils at 95.6 °C. Then vapourization of turpentine becomes easy and the immiscible liquid is collected separately. Steam distillation is used to separate/purify the liquids, such as clove oil, eucalyptus oil, almond oil, camphor, etc. Molecular distillation is a method in which each molecule of vapour phase travels mean path and gets condensed individually, before undergoing molecular collisions. In this method, condensation is handled with care. Normally, vapour molecules individually travel and get condensed. Even in simple distillation, collisions occur before condensation, but its impact is not significant. In this case, if vapour phase molecules collide, these turn into liquid and reach the distillation still (rather than getting condensed). Since the liquids have high boiling points (low vapour pressure), once again large amount of heat is supplied for vaporization. The separation is achieved (by lowering the boiling point) by applying vacuum. Further the condenser is placed very close to the liquid surface such that as soon as the liquid is vapourized, the short free path is travelled and gets condensed. Thus, molecular distillation permits the separation of liquids, namely free fatty acids, vitamin A and fixed oils.

Glossary of Symbols

P = Total vapour pressure of the mixture, kPa.
p = Partial vapour pressure of a liquid, kPa.
p° = Vapour pressure exerted by pure solvent, kPa.
v = Volatility of the component, kPa.
X = Mole fraction of component in liquid state.
Y = Mole fraction of component in gaseous state.
α = Relative volatility.
ρ = Density, kg/m^3.
η = Viscosity, Pa.s.

QUESTION BANK

Each question carries one mark

Note : Encircle the alphabet which corresponds to the single best response.

1. Distillation operation involves one of the following steps.
   A. Vapourisation
   B. Vapourisation and condensation
   C. Vapourisation, condensation and crystallisation
   D. Vapourisation, condensation, crystallisation and drying
2. Separation of liquid by distillation is based on one of the following principles?
   A. Boiling point B. Miscibility
   C. Vapour pressure D. Viscosity
3. Absolute alcohol is prepared by one of the following methods.
   A. Azeotropic distillation B. Simple distillation
   C. Steam distillation D. Vacuum distillation
4. One of the following theories is NOT applicable to distillation.
   A. Graham's law of diffusion
   B. Law of conservation of energy
   C. Law of conservation of matter
   D. Raoult's law
5. Distillation does NOT involve in one of the following processes.
   A. Evaporation B. Extraction
   C. Purification D. Separation
6. Raoult's law is applicable to one of the following type of distillation processes.
   A. Flash distillation B. Fractional distillation
   C. Molecular distillation D. Simple distillation
7. Which part in the distillation apparatus represents heat exchanger?
   A. Adopter B. Condenser
   C. Receiver D. Still
8. Which law satisfies the batch type distillation of a binary system for separation?
   A. Dalton's law B. Raoult's law
   C. Rayleigh's law D. Stokes law
9. Which one of the methods is also known as differential distillation?
   A. Azeotropic distillation B. Molecular distillation
   C. Simple distillation D. Steam distillation

10. Which is the distillation known as dry distillation?
    A. Compressive distillation
    B. Destructive distillation
    C. Evaporative distillation
    D. Steam distillation
11. Which one of the following methods is used for the distillation of camphor?
    A. Azeotropic distillation
    B. Evaporative distillation
    C. Fractional distillation
    D. Steam distillation
12. Steam distillation is NOT suitable when:
    A. aromatic water is required to be prepared
    B. boiling point of liquid is high
    C. immiscible liquid and water do not react with each other
    D. immiscible liquid and water react with each other
13. Which type of liquid evaporates first in the distillation?
    A. Immiscible liquid
    B. Less volatile liquid
    C. More volatile liquid
    D. Non-volatile liquid
14. Which liquid (substance) distils first among the following?
    A. Benzene
    B. Glycerine
    C. Phenol
    D. Toluene
15. Which substance is added for the separation of butadiene from a mixture of butane containing butane?
    A. Benzene
    B. Ethanol
    C. Furfural
    D. Glycerine
16. Which type of distillation is used for the preparation of aromatic spirit of ammonia?
    A. Flash distillation
    B. Fractional distillation
    C. Molecular distillation
    D. Simple distillation
17. Vacuum pump is attached to one of the following parts of the distillation apparatus?
    A. Adopter
    B. Condenser
    C. Receiver
    D. Still
18. The condenser used for the distillation has one of the following characteristics?
    A. Easy to clean
    B. Large surface area
    C. Positioned inclined
    D. Positioned upright
19. Water for injection is prepared using one of the following distillation methods?
    A. Flash distillation
    B. Fractional distillation
    C. Simple distillation
    D. Steam distillation

20. Complete separation of individual components is NOT possible in one of the distillation methods?
    A. Azeotropic distillation
    B. Flash distillation
    C. Steam distillation
    D. Vacuum distillation
21. Which one of the following liquid systems is involved in azeotropic distillation?
    A. Four component system
    B. One component system
    C. Three component system
    D. Two component system
22. Malt extract is prepared by adopting one of the following distillation methods?
    A. Molecular distillation
    B. Simple distillation
    C. Steam distillation
    D. Vacuum distillation
23. Claisen flask for distillation consists of one of the following number of necks?
    A. Four
    B. One
    C. Three
    D. Two
24. Which type of distillation is known as evaporative distillation?
    A. Flash distillation
    B. Fractional distillation
    C. Molecular distillation
    D. Simple distillation
25. Which one of the following distillation methods is known as equilibrium distillation?
    A. Flash distillation
    B. Fractional distillation
    C. Molecular distillation
    D. Simple distillation
26. In distillation apparatus, condenser functions as one of the following.
    A. Energy exchanger
    B. Heat exchanger
    C. Liquid exchanger
    D. Material exchanger
27. Generally condenser is placed in inclined position for one of the following reasons?
    A. Collect the condensate easily
    B. Fast condensation
    C. Remove the film of condensed liquid
    D. Use of gravity principle effectively
28. Better separation of liquid can be achieved by steam distillation, if one of the conditions is satisfied.
    A. Relative volatility of liquid is higher
    B. Relative volatility of liquid is lower
    C. Volatility of liquid is higher than steam
    D. Volatility of liquid is lower than steam
29. The liquid is allowed to pass suddenly, from a zone of high pressure to a zone of low pressure in one of the following distillation methods.
    A. Flash distillation
    B. Fractional distillation
    C. Molecular distillation
    D. Vacuum distillation

30. If the external pressure is reduced by applying vacuum, boiling point of liquid follows one of the following conditions.
    A. Decreases B. Decreases and increases
    C. Increases D. Remain unchanged
31. Molecular distillation is used for the purification of one of the following substances.
    A. Carbohydrates B. Fats
    C. Proteins D. Volatile oils
32. The process of distillation of solution containing thermolabile substances is achieved by:
    A. Destructive distillation B. Fractional distillation
    C. Simple distillation D. Vacuum distillation
33. Mean free path is associated with:
    A. azeotropic distillation B. destructive distillation
    C. molecular distillation D. steam distillation
34. Equilibrium distillation is also known as:
    A. azerotropic distillation B. flash distillation
    C. molecular distillation D. steam distillation
35. Falling film molecular still is:
    A. distillation apparatus B. dryer
    C. evaporator D. fitter
36. Which distillation method is used for the separation of high boiling substances from non-volatile impurities?
    A. Rectification distillation B. Simple distillation
    C. Steam distillation D. Vacuum distillation
37. Florentine receiver is used to separate the liquids based on:
    A. density B. molecular weight
    C. sedimentation rate D. volatility
38. A mixture of acetone and methanol can be separated by one of the following distillation methods.
    A. Fractional B. Simple
    C. Steam D. Vacuum
39. In steam distillation, the sum of vapour pressure of the volatile component and water is related to atmospheric pressure in one of the ways.
    A. Equal B. Exactly half
    C. Less D. more
40. Steam distillation is used for the separation of:
    A. Essential oils B. Fatty acids
    C. Mineral acids D. Petroleum fractions

Each question carries 2 marks

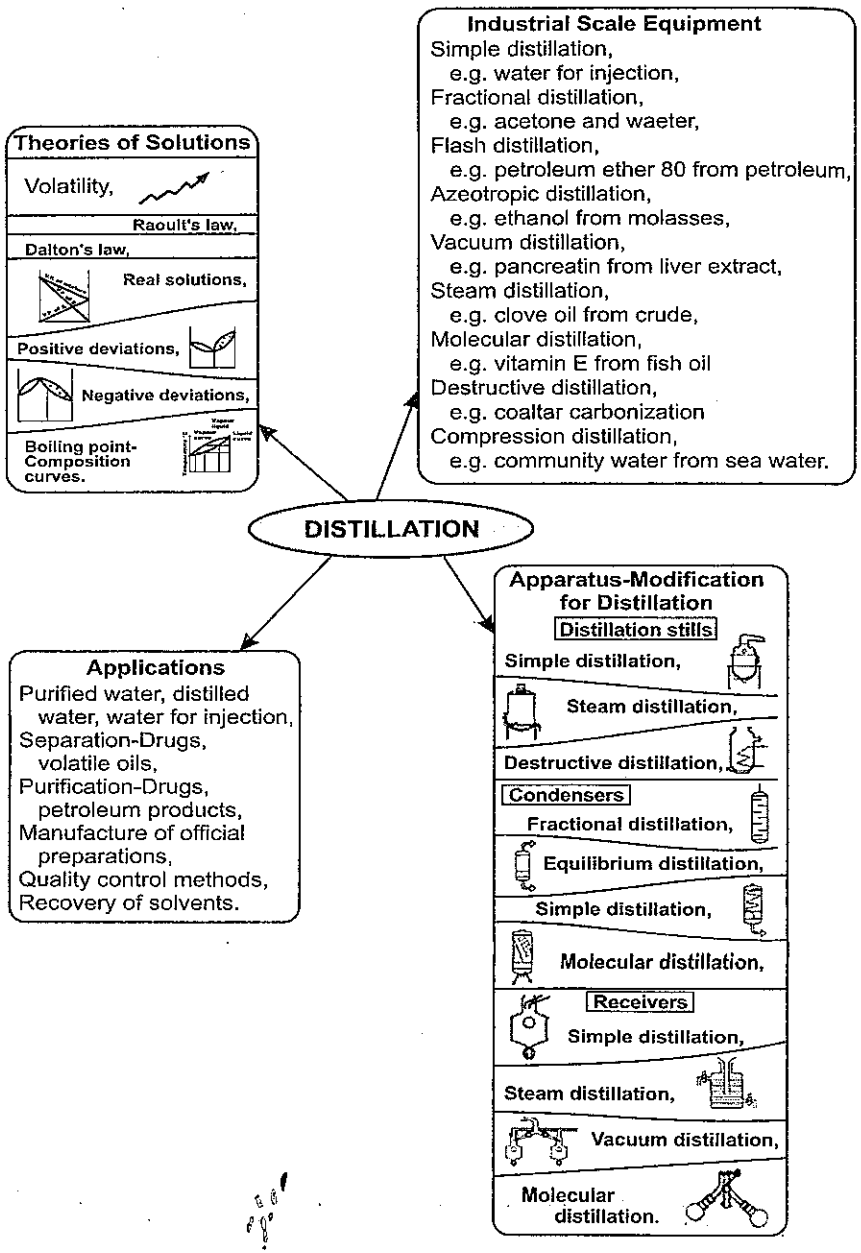
1. Describe Raoult's law. What is its significance?
2. What are constant boiling mixtures? How are they separated?
3. What is meant by constant boiling mixtures? Give two examples.
4. Name the materials commonly used in packing of fractionating columns.
5. List the requisite characteristics that a packing material should possess.
6. Differentiate between plate towers and packed towers.
7. Describe the construction of any one fractionating column.
8. Distinguish between drying and distillation. Explain differential distillation.
9. Distinguish between 'stripping section' and 'rectifying section' of a rectifying column.
10. Name the characteristics of a packing material for use in fractionating columns.
11. Name different types of rectifying columns.
12. Define distillation. Mention two applications of it as per IP.
13. Differentiate between differential distillation and rectification.
14. Define 'ideal plate' and 'relative volatility'.
15. Define 'flash distillation'. List applications.

Each question carries 5 marks

1. Explain with relevant procedure the separation of an azeotropic mixture.
2. What is meant by steam distillation? What are its special advantages?
3. Describe the principles and applications of steam distillation.
4. What are constant boiling mixtures? Draw typical boiling diagrams for constant boiling mixtures.
5. Describe the construction of bubble cap column. What are its advantages?
6. Describe a bubble cap rectifying column. What are the specific drawbacks of bubble cap columns?
7. Describe one fractionating column of your choice. List its advantages and disadvantages.
8. Describe the construction and working of a distillation apparatus for the preparation of distilled water.

Each question carries 10 marks

1. Explain the principle and procedure of molecular distillation. What are its applications?
2. Distinguish between plate columns and packed towers. Describe the types of packing for rectifying columns. How is absolute alcohol made?



MINDMAP OF DISTILLATION

CHAPTER 8

Drying

Theory of Drying
Classification of Drying Equipment
Equipment
Selection of the Drying Equipment

LEARNING OBJECTIVES

After reading this chapter, the reader should be able to:

- Appreciate the principles of drying with applications.
- Explain the concepts involved in terms of mechanisms, moisture content, drying rate, drying curves.
- Describe different designs of industrial scale drying equipment along with working and uses.
- Select a suitable drying equipment for materials of given properties.

Drying is defined as the removal of small amounts of water or other liquid from a material by the application of heat.

Drying is a downstream operation and commonly utilized in the last stage of the process and thus has considerable importance. Drying means complete dryness or a condition known as air-dry or maintaining an acceptable level. The liquid can be organic such as chloroform, ethanol, and isopropanol. These solvents are present on account of synthesis, filtration and extraction. The solvent evaporation is necessary for the preparation of the API. The feed may be a solution or a suspension. Drying is also applied for removal of small quantities of water or liquid from gases, as in case of drying of gases. But this is not described in this chapter. The liquid medium may be removed from the solids mechanically by a filter press or centrifuge or thermally by vaporisation. It is cheaper to remove liquid by mechanically than thermally. Therefore, it is advisable to reduce the liquid as much as possible before subjecting to the drying process. The material to be treated is a solid and liquid is present in traces. However, methods such as spray drying are available in which solutions and suspensions can be processed for drying in one operation itself.

Drying is defined as the removal of all or most of the liquid by supplying heat to cause thermal vapourization.

Drying is a physical separation unlike filtration which is a mechanical separation. Drying and evaporation are distinguishable by the relative quantities of liquid removed from the solid. In evaporation, the product obtained is either concentrated solution or suspension or wet slurry. In drying, dry solid is the product. In evaporation, water is removed at its boiling point, but in drying, vapour is removed at a temperature below its boiling point.

The liquid to be vaporised may remain:

- on the surface of the solid, as in drying of salt crystals,
- entirely inside the solid, as in solvent removal from a sheet of polymer,
- partly outside and partly inside, as in case of solvent removal from pharmaceutical powders.

Drying is possible when the environment is unsaturated with the water vapour. Hence, humidity in the environment is an important determinant for drying of the solids. Though several methods are available, thermal methods and freeze drying technique (nonthermal method) are included here. This chapter deals with the theoretical principles and equipment employed for drying.

Heat Transfer Mechanisms

Most of the equipment design used heat as a form of energy for drying. All mechanisms of heat transfer can be considered (Chapter 5).

- **Conduction :** It is explained by Fourier's equation. The temperature gradient is the driving force for heat transfer. Modeling can be attempted by considering one direction.
- **Convection :** It involves the molecular scale transfer of kinetic energy and augmented by macroscopic movement of fluid transfer. Such a heat transfer is a complex mechanism, though empirically terms, natural or forced convection and expressed by the film coefficients.
- **Thermal radiation :** In this case, radiant energy is emitted by a medium by virtue of its temperature. The wavelength of thermal radiation falls between 0.1 and 100 μm, which includes portion of ultraviolet, visible and infrared spectra. The heat transfer rate is explained by Stefen Boltzmann equation.

Applications

The presence of water or organic solvent affects the downstream processing (compression of tablet mass or stability of API) and safety operations.

Preparation of bulk drugs : In the preparation of bulk drugs, drying is the final stage of processing. A few examples are:

- dried aluminium hydroxide
- spray dried lactose
- powdered extracts

Drying step is essential after certain operations such as crystallization and filtration.

Preservation of drug products : Drying is necessary in order to avoid deterioration. A few examples are:

Crude drugs of animal and vegetable origin	– chemical decomposition
Blood products, skin, tissue	– microbial growth
Synthetic and semisynthetic drugs	– chemical decomposition
Effervescent tablets (aspirin, penicillins)	– chemical decomposition

Improved characteristics : Drying produces materials of spherical shape, uniform size, free flowing and enhanced solubility.

Some specific areas of importance are:

(1) Granules are dried to improve the fluidity and compression characteristics. These are essential for the production of tablets and capsules.

(2) Viscous and sticky materials are not free flowing. Drying modifies these characteristics. e.g. male fern extract, malt extract and oleoresin.

Improved handling : Removal of moisture makes the material light in weight and reduces the bulk. Thus cost of transportation will be less and storage will be efficient. If moisture is present, size reduction of drugs is difficult. Drying reduces the moisture content.

Comment 8-1. Drying of solids prevents deterioration of drugs. Justify.

THEORY OF DRYING

In a wet solid mass, water may be present as bound water and unbound water.

Bound water (moisture) is the minimum water (moisture) held by the material that exerts an equilibrium vapour pressure less than the pure water at the same temperature.

Unbound water (moisture) is the amount of water (moisture) held by the material that exerts an equilibrium vapour pressure equal to that of pure water at the same temperature.

During drying process, water is easily lost, but the resulting solid is not completely free from water molecules. This is known as *air-dry*. Easily removable water is the unbound water at the defined environmental conditions. After removal of water completely, the material is said to be '*bone-dry*'.

Unbound water exists largely in the voids of the solid. Thus, in a non-hygroscopic material, all the liquid is unbound water. In a hygroscopic material, the unbound moisture is the liquid in excess of the equilibrium moisture content, corresponding to saturation humidity. Substances containing bound water are often called *hygroscopic substances*. The distinction between bound and unbound water depends on the material itself. These are described in Figure 8-1.

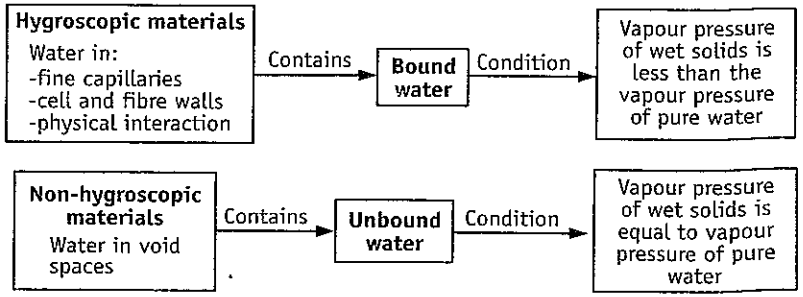


Figure 8-1. Differences of bound and unbound water.

Heat must be transferred to the material to be dried in order to supply the latent heat required for vaporisation of the moisture. Water diffuses through the material to the surface and subsequently evaporates into the air stream. Thus drying involves both heat transfer and mass transfer operations simultaneously.

Theory can be discussed in three heads namely mechanisms of drying, equilibrium relationships and rate relationships.

Mechanisms of Drying Process

Into the dryer, warm air stream is introduced to provide the latent heat. This heat is taken up by the material and the moisture evaporates. Drying involves both heat transfer and mass thereby making the analysis a complex process transfer processes simultaneously. Drying is a three step process:

1. Heat transfer takes place from the heating medium to the solid material.

2. Mass transfer involves the transfer of moisture to the surface of the solids and subsequently vapourisation from the surface into surroundings.
3. Transfer of the released vapour away from the pharmaceutical material and out of drying equipment.

The recovery of solvent is not normally attempted. Various theories are proposed to explain the movement of moisture.

(1) Diffusion theory
(2) Capillarity theory
(3) Pressure gradient theory
(4) Gravity flow theory
(5) Vapourisation and condensation mechanisms

A few of these theories are explained in the following sections.

Diffusion theory : Diffusion theory assumes that the effect of capillarity, gravitational, and friction forces are too small. In diffusion theory, the rate of flow of water is proportional to moisture gradient. According to this theory, moisture movement may be as follows.

- Water diffuses through the solid to the surface and subsequently evaporates into the surroundings.
- Evaporation of water occurs at an intermediate zone, much below the solid surface, then vapours diffuse through the solid into air.

Due to limitations in predicting the drying rate over a range of moisture gradients, this theory is not much applicable.

Limitations : Diffusivity decreases as the moisture content and temperature decreases, while increases with pressure.

Capillarity theory : Capillarity theory is applicable to porous granular solids. Porous material contains a network of inter-connected pores and channels, which are not circular or straight. At the surface, the cross-section of these capillaries forms various sizes of pores. As the drying starts, a meniscus is formed in the capillary and exerts a force. This is the driving force for the movement of water through pores towards the surface. The curvature of the meniscus depends on the pore diameter and determines the strength of capillary force. The capillary force is greater in small pores compared to the large pores. Therefore, small pores pull more water from the larger pores and thus large pores get emptied first. Air enters into the emptied pores and the moisture content is relatively higher near the surface.

Capillary theory holds good only for free water in the bed. This type of movement of liquid takes place in the granules (pores) as well as in the spaces between the granules (void spaces). As the pore diameter is con-

siderably smaller inside a granule than the surrounding granules, liquid surrounding the granules can be removed initially. Then pore liquid inside a granule is vapourized. Diffusion theory is applicable to hygroscopic material.

Pressure gradient theory : Pressure gradient theory is applicable to drying of solids by the application of radiation (not external heating). Radiation is a source for generating internal heat. The radiation interacts with the polarized molecules and ions of the material. This field aligns the molecules in order, which are otherwise randomly oriented. When the field is reversed, the molecules return to the original orientation. In this process, it gives up random kinetic energy (or heat) to the inside surface of the solids itself. Therefore, liquid inside the solids is vapourised. As a result, vapour pressure gradient is developed which is the driving force for the movement of vapour to the surface.

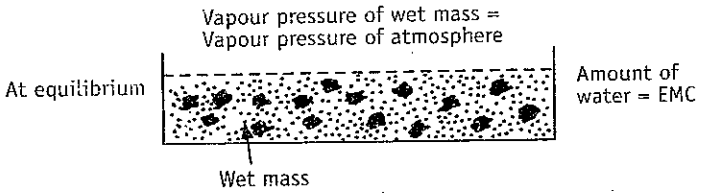
This type of drying mechanism is applicable to radiation drying, provided such rays penetrate deep inside the solid mass.

Equilibrium Relationships

Air of constant temperature and humidity is passed over the wet solid. After a long exposure, equilibrium is reached. On attaining equilibrium, further exposure will not alter moisture content in the solid. At this stage, vapour pressure of the wet solids is equal to that of the surrounding atmosphere. Hence there is no driving force for mass transfer.

Equilibrium moisture content (EMC) : It is the amount of water present in the solid which exerts a vapour pressure equal to the vapour pressure of the atmosphere surrounding it.

The moisture (content) which is more difficult to remove in practice is the equilibrium moisture content. This moisture content is retained by the solid under steady state conditions. This water (or liquid) does not vapourize and does not produce vapour pressure. From that point, full vapour pressure cannot be developed. Equilibrium moisture content in a wet mass is shown below.

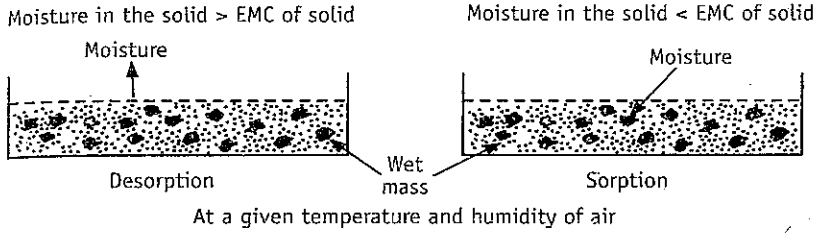


The characteristics of air such as temperature and humidity are maintained constant. Depending on these conditions, the solids may absorb or lose moisture.

(a) When air (of constant temperature and humidity) is continuously passed over the solid containing moisture more than EMC, then solid loses water continuously till EMC is reached. This phenomenon is known as *desorption*.

(b) When air (of constant temperature and humidity) is continuously passed over the solid containing moisture less than EMC, then solid adsorbs water continuously till EMC is reached. This phenomenon is known as *sorption*.

The behaviour of desorption and sorption is shown below. From the above observations it is clear that, material can be dried up to EMC but not below it.



Measurement of EMC : The EMC of a material can be determined as follows. The solid samples are placed in a series of closed chambers such as desiccators. Each chamber consists of solution (desiccant), which maintains a fixed relative humidity in the enclosed air spaces. In other words, the solid samples are exposed to several humidity conditions. The exposure is continued until the material attains a constant weight (equilibrium conditions). The difference in the final and initial weights gives the moisture content. The moisture content is measured twice; before keeping the material into the storage bin and while taking out the material for processing the next step (compression). During storage, the material may lose/gain moisture. Many materials have inherent properties of gaining (hygroscopic) or loosing (efflorescent) of moisture even during storage.

Equilibrium moisture curve is drawn by taking relative humidity (%) on x-axis and moisture content on y-axis (Figure 8-2).

Application of EMC : The EMC curve permits the selection of the experimental conditions to be used for drying the product. Drying should be stopped when the moisture content reaches the level of the EMC under the exposed conditions. Over drying can be avoided, because over-dried solid quickly regains the moisture from the ambient conditions.

If the moisture content is to be reduced, the relative humidity of the ambient air must be reduced as a first step. This can be done mechanically on a large scale using an air-conditioning system. On a small scale,

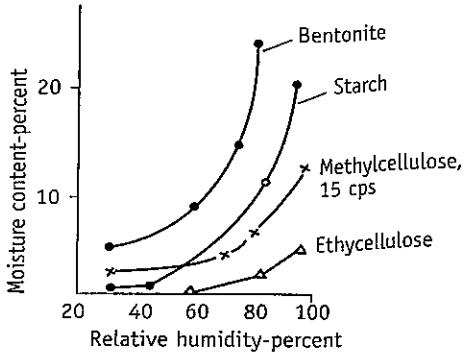


Figure 8-2. EMC curves for materials.

desiccators are employed. Some materials, such as tablet granules, have superior compaction properties with a small amount (1-2 %) of residual moisture content.

Factors affecting EMC : EMC values vary depending on a number of factors.

Nature of material:

(1) Nonporous insoluble solids have an EMC of practically zero. e.g. talc and zinc oxide.

(2) For fibrous or colloidal organic substances, the EMC values are high and variable. For example, cotton fabric has high EMC (10 to 15 %) under normal atmospheric conditions.

(3) For porous solids, the EMC values are much higher and variable. The water may be held in fine capillaries that have no access to the surface. The dissolved solid may reduce the vapour pressure and water may be molecularly bound.

Nature of air:

(1) For air of zero humidity, EMC of all materials is zero.

(2) As the temperature of air increases, the EMC of solid decreases.

EMC of solids is a constant for a given temperature and humidity of air. If the equilibrium curves (Figure 8-2) are continued up to 100 % RH, the moisture content so obtained (EMC with saturated air) is the least moisture at which the material can exert a vapour pressure as high as that exerted by liquid water at the same temperature. If the material is unstable to moisture at the EMC levels, then drying is deliberately conducted below EMC under room conditions. Based on these properties, the storage conditions are specified after drying. The storage conditions are not critical for some products, e.g. lactose granules. Moisture is avoided in case of

ascorbic acid granulation. If an antacid formulation is stored at 65 % RH for sufficient period, the formulation absorb moisture and becomes sticky. This leads to poor flow and poses difficulties in compression of tablets.

Free moisture content (FMC) : *Free moisture content* (FMC) is the amount of water that is free (easy) to evaporate from the solid surface.

Under the conditions of saturation humidity (100 % RH), the EMC is the minimum moisture content. Under these conditions the water must be bound water which is minimum at that temperature. The remaining is unbound for which the FMC for a given condition can be written as:

Free moisture content (FMC) = total water content – equilibrium moisture content (EMC)

The distinction between free and equilibrium moisture depends on the drying conditions.

Rate Relationships

Rate relationships can be studied by considering a simple model, which mimic the conditions of a dryer, i.e. static bed dryer. In this model, wet slab of material of sufficiently high moisture content to be dried is placed in a tray whose bottom and sides are insulated. The air is blown over the solid under constant drying conditions (air velocity, temperature, humidity and pressure. The superficial water diffuses through the surrounding stationary air film and is carried away rapidly by the moving air stream.

During drying, the surface temperature falls to the wet-bulb temperature that corresponds to the temperature and humidity of air.

The rate of transfer of water vapour from the surface into air is:

$$N = \frac{k_g}{RT}\,(p_{wi} - p_{wa}) \qquad \ldots(1)$$

where p_{wi} = partial pressure of water vapour at the surface, mPa

p_{ws} = partial pressure of water vapour in the air, mPa

N = moles of vapour transferred per unit area in unit time

R = Ideal gas constant, kJ/kmol.K

T = absolute temperature, K

k_g = mass transfer coefficient, mol per unit area

The k_g mass transfer coefficient is a function of:

- temperature
- air velocity
- angle of air incident

The mass of liquid per unit time (w) is expressed by rewriting equation

(1) as:

$$w = \frac{M_w \times A}{RT} k_g (p_{wi} - p_{wa}) \quad ...(2)$$

where M_w = molecular weight of water vapour (18 g/mol)

High velocity or angle of incidence diminishes the thickness of the stationary air layer in contact with the liquid surface, thereby lowering the diffusional resistance.

The rate of evaporation may also be expressed in terms of heat transfer across the laminar film from the drying gases as:

$$Q = hA (T_a - T_s) \quad ...(3)$$

where Q = rate of heat transfer, J/s
h = heat transfer coefficient, J/s.m^2.K
A = area of surface, m^2
T_a = temperature of drying air, K
T_s = temperature of the surface, K

Equation (3) refers across the laminar flow from drying gases to the surface. The heat transfer coefficient is also a function of air velocity and the angle of impingement.

Actually mass transfer rate (w) occurred due to the latent heat of evaporization (λ) is:

$$w = \frac{hA}{\lambda} (T_a - T_s) \quad ...(4)$$

When these conditions pertaining to drying, the surface temperature, T_s (though consider as equal to the wet-bulb temperature), is normally much lower than the temperature of drying gases. The observation is applicable to drying of thermolabile substances. If solids are present in the surface, the rate of evaporation is modified, then the overall effect depends on the structure of the solids and the moisture content.

Periodically the slab is weighed. The difference in the weights of two successive periods gives the loss of moisture content, i.e. amount dried. The moisture present in the solid can be expressed on a wet weight or dry weight basis. Then the following calculations are made:

$$\% \text{ Loss on drying (LOD)} = \frac{\text{mass of water in sample (kg)}}{\text{total mass of wet sample (kg)}} \times 100$$

$$\% \text{ Moisture content (MC)} = \frac{\text{mass of water in sample (kg)}}{\text{mass of the dry sample (kg)}} \times 100$$

$$\text{Drying rate} = \frac{\text{weight of water in sample (kg)}}{\text{time (h)} \times \text{weight of the dry solid (kg)}}$$

Drying rate is plotted against the midpoints of the time period. Similarly midpoints of the moisture content values can be plotted.

From the data obtained by the above experiment, a graph is plotted by taking FMC on x-axis and drying rate on y-axis. The curve so obtained (Figure 8-3) is called *drying rate curve*. It represents different changes during drying as explained below.

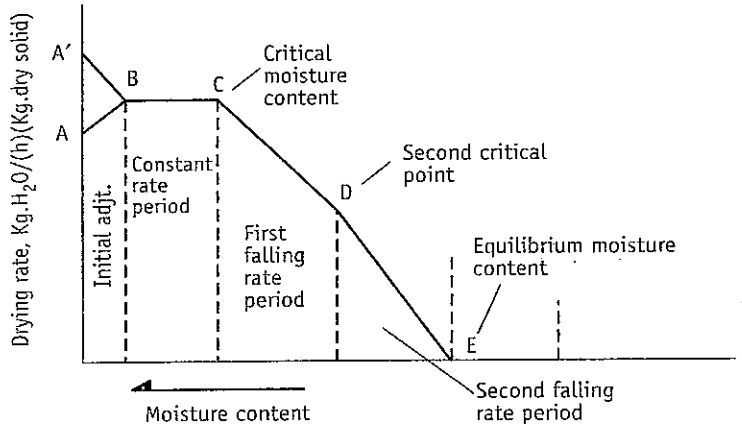
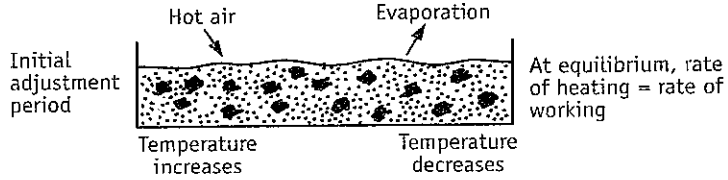


Figure 8-3. FMC curve.

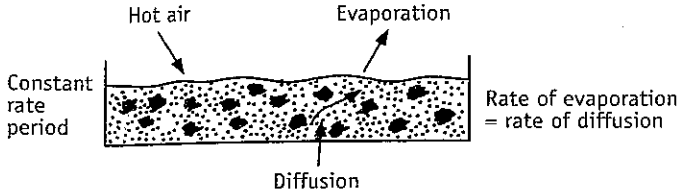
(1) The time corresponding to A$\dot{B}$ represents the *initial adjustment period*. During this period, the solids absorb heat and the temperature increases. At the same time, the moisture begins to evaporate and thus tends to cool the drying solid. After some time, the temperature stabilises (heating and cooling rates become equal). This temperature is equal to the wet bulb temperature of the drying air and is referred by the point B. A′B represents a drying period when the sample is taken from reactor at high temperature to a dryer at a low temperature.



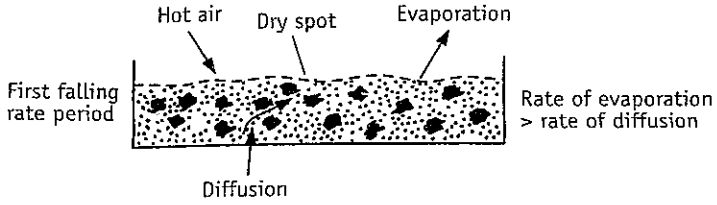
(2) The time corresponding to BC represents the *constant rate period*. The temperature remains constant and rate of drying is constant. The moisture evaporating from the surface is replaced by the water diffusing from

the interior of the solid. The rate of diffusion is equal to the rate of evaporation. This is similar to the evaporation of plain water surface (saturated surface). At this stage the temperature is similar to wet bulb temperature. When all other variables are kept constant, the constant drying rate is independent of the material being dried. As the water is freely removed, particle size of the solids influences the drying rate. The moisture content at the end of constant rate (point C) is referred to as the *critical moisture content* (CMC).

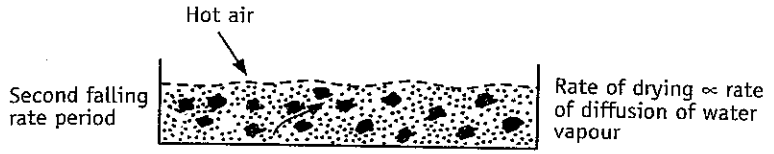
Critical moisture content is a point below which the movement of moisture from the interior is no longer sufficient to saturate the surface. For any material, critical moisture content decreases with decreasing the particle size (increase in surface area).



(3) The time corresponding to CD represents the *first falling rate period* (or unsaturated surface drying). During this period, the surface water is no longer replaced at a rate fast enough to maintain a continuous film on the surface. Dry spots begin to appear and the rate of drying begins to fall off. For first-falling rate period, the temperature of the solid surface is above the wet-bulb temperature. The point D is referred to as the *second critical point*. At this point, the film of surface water is completely evaporated.



(4) The time corresponding to DE represents the *second falling rate period*. During this period, the rate of drying falls even more rapidly than the first falling rate. During this period, the rate of drying is dependent on the rate of diffusion of vapour of moisture to the surface of the solid. The rate of drying is largely independent of the conditions outside the bed, but markedly affected by the particle size. During the period, the surface temperature approaches the temperature of dry air. Point E is referred to as the *equilibrium moisture content.*



(5) Beyond E, the drying rate is equal to zero. Therefore, temperature and moisture content remain constant. Beyond, E, continued drying is waste of time and energy.

The drying process is related to wet-bulb and dry-bulb temperatures. Drying (migration of liquid) largely occurs during the constant-rate period and first falling-rate period. As drying continues, crystallization also occurs to a certain extent, though it is not the objective. If the ingredients are water soluble, then segregation of the soluble ingredients occur during drying. Therefore, blending is essential after drying (dry blending). The curves may have different shapes for different levels of moisture. If the drying is carried above the level of CMC, only constant rate period occurs. If the drying is started for the material whose initial moisture content is less than CMC, then falling rate period occurs.

The falling rate periods put together gives nearly a linear plot and hence possible to model the drying process. A simplified equation is:

$$\ln \frac{M_t}{M_0} = -kt - 0.2$$

where k = first order rate constant, h^{-1}
M_0 = moisture content at initial period, kg (g)
M_t = moisture content (mass) at any time t, kg (g)

A plot is drawn by taking ln (M_t/M_0) on y axis and time on x axis. A straight line is obtained with a negative slope, $-k$. This model permits the evaluation of drying process in a tray dryer and impact of process parameters (bed thickness and drying temperature). Drying can be attempted at different temperatures and a relationship can be drawn between ln k vs. $1/T$ (a pattern similar to Arrhenius plot for drug loss against temperature), i.e. moisture loss against temperature.

Comment 8-2. How is desorption different from sorption?

Comment 8-3. How is the ending of first falling drying rate period identified?

Comment 8-4. EMC values of all the substances remain same. True or false. Explain.

CLASSIFICATION OF DRYING EQUIPMENT

The classification based on the method of solids handling is more suitable when special attention is given to the nature of material to be dried. Dryers are classified as given in Table 8-1.

TABLE 8-1
Classification of Dryers—Mechanism, Examples, Advantages and Disadvantages

Type of dryer and mechanism	*Examples*	*Advantages*	*Disadvantages*
Static Bed Dryer Systems in which there is no relative movement among the solid particles being dried, although there may be bulk motion of the entire drying mass.	Tray dryer and freeze dryer	Attrition is not observed	Only a fraction of the solid particles is directly exposed
Moving Bed Dryer Systems in which the drying particles are partially separated so that they flow over each other	Drum dryer	The entire material is continuously exposed to heat source	Attrition is possible
Fluidised Bed Dryer Systems in which the solid particles are partially suspended in an upward moving heated gas system	Fluidised bed dryer	Solid-gas contact is excellent, uniform drying	Attrition of particles takes place
Pneumatic Dryer Systems in which drying particles are entrained and conveyed at a high velocity gas stream	Spray dryer	Efficient and rapid drying	Attrition of particles takes place

As per the principal mole of operation (regulatory guidance document), dryers are classified as follows.

Direct heating dryers : These allow intimate contact between the material being dried and the heat energy source (heated gas). The same gas is allowed to transport the vapour released from the material. E.g. tray dryer and fluidized bed dryer.

Indirect heating dryers : In this type, energy is transferred from the source (heated liquid) to the material being dried through a conducting wall. E.g. vacuum dryer and drum dryer. Indirect dryer would also be needed when a material requires absolute sterility, for example, sterile solid for injection or reconstitution with sterile water.

Radiant heating dryers : In this type, radiation is absorbed by the solvent being targeted for removal, e.g. microwave dryer and IR dryer.

The classification of dryer is given in Table 8-2. In the formulation manufacture, continuous dryer is rarely used, tray dryer and drum dryer

are useful. The cost of the drying is high. In a tray dryer, heat is directly applied to the material, via a stream of hot gas. An indirect dryer, however, transfers the heat through the shell to the material, e.g. rotary drum dryer. For example, some household items need to be safe for being around children.

TABLE 8-2
Classification of Dryers Based on the Scale of Drying

Batch type dryer	*Continuous dryer*
Tray dryer	Drum dryer
Vacuum dryer	Spray dryer
Fluid bed dryer	
Agitated batch dryer	
Tumbling dryer	
Freeze dryer	

Critical Quality Attributes — Drying

The critical quality attributes (CQAs) and process parameters (PPs) are recorded in Figure 8-4. The drying operation is considered for the production of tablets. The upstream operation must be granulation and the downstream operation is dry blending with lubricants (for compression). For a given set of conditions, the following attributes are considered as critical.

Moisture content – compression requirement
Flow properties – content uniformity
Bulk/tapped densities – size of tablet, flow, content uniformity
Residual solvent – impurity profile
Yield – production economy (viability)

The CQAs have two reasons—(a) facilitate the downstream operation and (b) achieve the final product CQAs. The process parameters are optimized and these are related to economy as:

load size, time of drying, drying rate

These are controlled during the unit operation and are prefixed as standards with limits for a given set of conditions. Production control charts can be used for monitoring the parameters. The above are general attributes, but change depends on the drying equipment type, as the principles of drying varies, such as vacuum application, fluidization, static or moving, etc. Further removal of water or hydro-alcohol and nature of solids are considered. The environment (temperature and relative humidity) are maintained for production and storage.

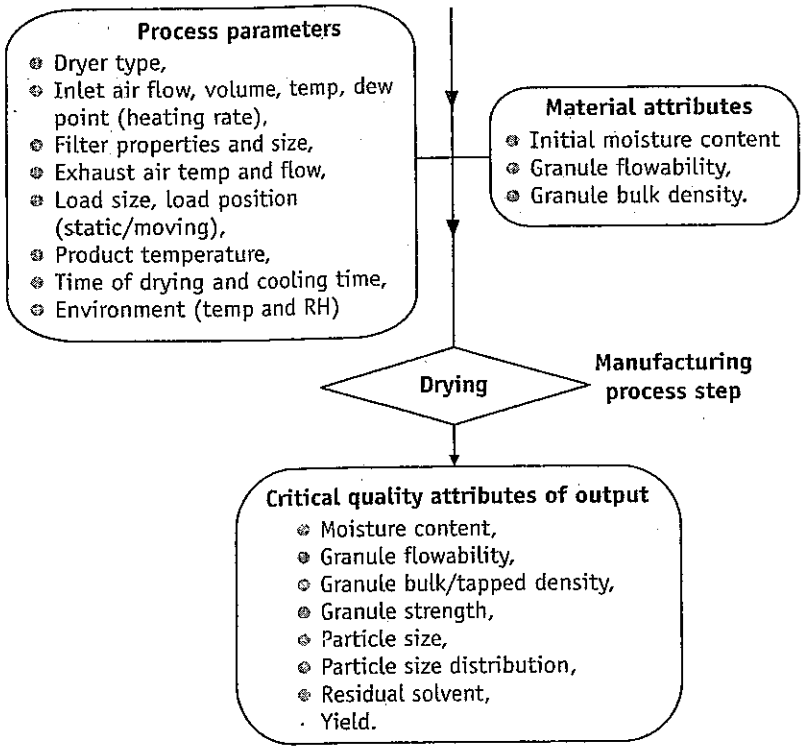


Figure 8-4. Process parameters and critical quality attributes for drying operation in the product development of tablets.

EQUIPMENT

Tray Dryer

Principle : In tray dryer, hot air is continuously circulated. Forced convection heating takes place to remove moisture from the solids spread in trays. Simultaneously, the moist air is removed partially.

Construction : The construction of a tray dryer is shown in Figure 8-5. It consists of a rectangular chamber whose walls are insulated. Trays are placed inside the heating chamber. The number of trays may vary with the size of the dryer. Dryers of laboratory size may contain a minimum of three trays, whereas dryers of industry size may contain more than 20 trays. Each tray is rectangular or square and about 1.2 to 2.4 m^2 in area. Trays are usually loaded from 10.0 to 100.0 millimetres deep. The distance between the bottom of upper tray and (upper) surface of the substance loaded in the subsequent tray must be 40.0 mm.

Alternately the trays can be placed in trucks on wheels, which can be rolled into and out of chamber. Two such trucks can be arranged inside dryer. Dryer is fitted with a fan for circulating air over the trays. Electrically heated elements are provided inside (rather than outside) to heat the air (steam also can be used as it is cheaper). The thermal efficiency is improved using finned tubes. Air temperature is thermostatically controlled between 40 and 120 °C. The heat is controlled manually by setting dampers and a common operating position gives 90 % recirculation and 10 % bleed-off. Heat blank is placed in such a position so as to prevent the radiant heat reaching the solids. In the corner of the chamber, vanes (not shown in Figure 8-5) are placed to direct air in the expected path.

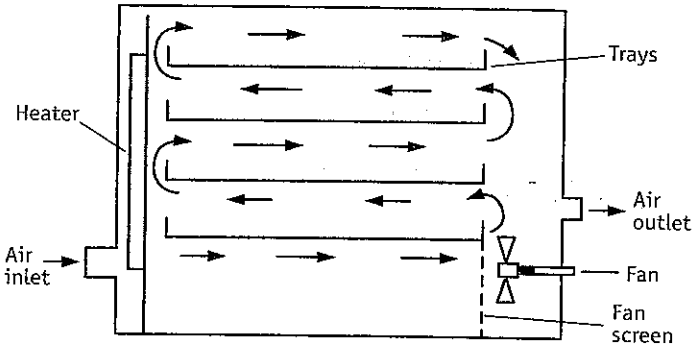


Figure 8-5. Tray dryer.

Working : Wet solid is loaded into trays. Trays are placed in the chamber. Fresh air is introduced through inlet, which passes through the heaters and gets heated up. The hot air is circulated by means of fans at 2 to 5 m/s. Turbulent flow lowers the partial vapour pressure in the atmosphere and also reduces the thickness of the air boundary layer. The water is picked up by air. As water evaporates from the surface, the water diffuses from the interior of the solid by capillary action. These events occur in a single pass of air. The time of contact is short and the amount of water picked up in a single pass is small. Moist air is discharged through outlet. Thus constant temperature and uniform airflow over the material can be maintained for achieving uniform drying.

In case of wet granules (as in tablets and capsules) drying is continued until the desired moisture content is obtained. At the end of drying, trays (trucks) are pulled out of the chamber and taken to a tray dumping station.

Uses : Sticky materials, plastic substances, granular mass or crystalline materials, precipitates and pastes can be dried in a tray dryer. Crude drugs, chemicals, powders, tablet granules or parts of equipment are dried.

Advantages:

(1) In tray dryer, handling of materials (loading and unloading) can be done without losses.

(2) Tray dryer is operated batch-wise. Batch drying is used extensively in the manufacture of pharmaceuticals for the following reasons.
   (a) Each batch of material can be handled as a separate entity.
   (b) The batch sizes in the pharmaceutical industry are relatively small (250 kg or less per batch) compared with the chemical industry (1000 kg or more per hour).
   (c) The same equipment is readily adjusted for use in drying a wide variety of materials.
   (d) Valuable products can be handled efficiently.

(3) Temperature can be adjusted to meet the conditions of thermosensitve materials.

Disadvantages : Tray dryer requires more labour to load and unload. Hence, cost increases. The process is time consuming. The dusty solid are not dried in a tray dryer. The design needs careful consideration to avoid non-uniform distribution of hot air over the trays. A variation of ±7 % in temperature is found from location to location.

Variants : Tray dryer may be operated under vacuum, often with indirect heating. This is done in special vacuum tray dryers for drying vitamins and other heat-sensitive products. In case of drying of granules, air can be passed downwards through the material laid on mesh trays. This facility reduces the drying time to 1 h or less. The tray dryer has become less popular, as more efficient and reproducible dryers are available, e.g. fluid bed dryer and vacuum dryer.

Tunnel dryer : In this type, trucks are loaded with wet material at one end of the tunnel. The tunnel comprised of a number of units, each of which is electro-statically controlled. The solids get dried and the product is discharged at the other end of the tunnel.

Drum Dryer or Roller Dryer (or Film Drum Dryer)

Principle : In drum dryer, a heated hollow metal drum rotates on its longitudinal axis, which is partially dipped in the solution to be dried. The solution is carried as a film on the surface of the dryer and dried to form a layer, on account of steam heated drum. A suitable knife scraps the dried material, while the drum is rotating. Mechanism is simple evaporation and no boiling is obtained.

Construction : The construction of a drum dryer is shown in Figure 8-6. It consists of a horizontally mounted hollow steel drum or chrome

plated steel of 0.6 to 3.0 m diameter and 0.6 to 4.0 m length, whose external surface is smoothly polished. These reduce contamination. Below the drum, feed pan is placed in such a way that the drum dips partially into the feed. On one side of the drum a spreader is placed and on the other side a doctor's knife is placed to scrap the dried material. A storage bin (or a conveyor) is placed connecting the knife to collect the material.

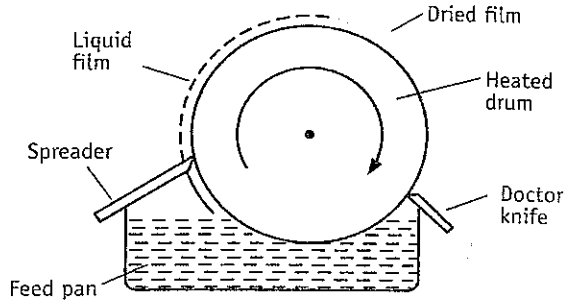


Figure 8-6. Drum dryer.

Working : Steam is passed inside the drum. Heat transfer coefficient of the drum metal is high. Drying capacity is directly proportional to the surface area of the drum. Heat is transferred by conduction to the material. Simultaneously drum is rotated at a rate of 1-10 revolutions per minute. The liquid material present in the feed pan adheres as a thin layer to the external surface of the drum during its rotation. The material is completely dried during its journey in slightly less than one rotation (i.e. from one side to another side of the drum). The dried material is scrapped by the doctor's knife, which then falls into a storage bin. The time of contact of the material with hot metal is 6 to 15 seconds only. Therefore, processing conditions such as film thickness, steam temperature are closely controlled.

The following parameters are closely controlled and monitored.

- Speed of drum dryer,
- Temperature of the feed,
- Film thickness,
- Steam temperature of the drum.

Uses : Drum dryer is used for drying solutions, slurries, suspensions, etc. The products dried are milk products, starch products, ferrous salts, suspensions of zinc oxide, suspension of kaolin, yeast, pigments, malt extracts, antibiotics, glandular extracts, insecticides, DDT, calcium and barium carbonates.

Advantages:

(1) In drum dryer, drying time is less, only a few seconds. Therefore, heat sensitive materials can be dried.

(2) Drum dryer occupies less space, as it is compact when compared to spray dryer.
(3) As a thin film of liquid is formed on the large heating surface, rates of heat transfer and mass transfer are high.
(4) The product obtained is completely dried and is in the final form.
(5) It is used for continuous drying/processing.

Disadvantages:

(1) The initial purchase cost and the maintenance cost of drum dryer are higher than spray dryer. Maintenance cost of a drum dryer is higher than spray dryer.
(2) Skilled operators are essential to control feed rate, film thickness, speed of rotation and temperature.
(3) It is not suitable for solutions of salts with less solubility.
(4) The heat treatment is higher than in spray drying. The solid product is less attractive. The liquid reaches the boiling point and the solid attain the drum temperature.

Variants : A vacuum drum dryer encloses both drum and feed line in a vacuum chamber to facilitate drying of heat sensitive materials. It is suitable for drying of drugs susceptible to oxidation and to recover solvents.

In a large scale, instead of one drum, two drums are set in parallel, rotating in opposite directions with a common feed inlet. The feed can be introduced on to the drum either by spraying it on the top or by introducing from the bottom.

Spray Dryer

Principle : In spray dryer, the fluid to be dried is atomized into fine droplets, which are thrown radially into a moving stream of hot gas. The heating medium (hot air) is in contact with the material (direct drying). The temperature of the droplets is immediately increased and fine droplets get dried instantaneously in the form of spherical particles. Drying takes place by simple evaporation rather than boiling. This process completes in a few seconds before the droplets reach the wall of the dryer.

Construction : The construction of a spray dryer is shown in Figure 8-7. It consists of a large cylindrical drying chamber with a short conical bottom, made up of stainless steel (diameter of the drying chamber ranges from 2.5 to 9.0 m and height is 25.0 m or more). An inlet for hot air is placed in the roof of the chamber. Another inlet carrying spray-disk atomizer is set in the roof (shown in Figure 8-7). The spray disk atomizer is about 300 m in diameter and rotates at a speed of 3,000 to 50,000 revolutions per minute. Bottom of the dryer is connected to a cyclone separator.

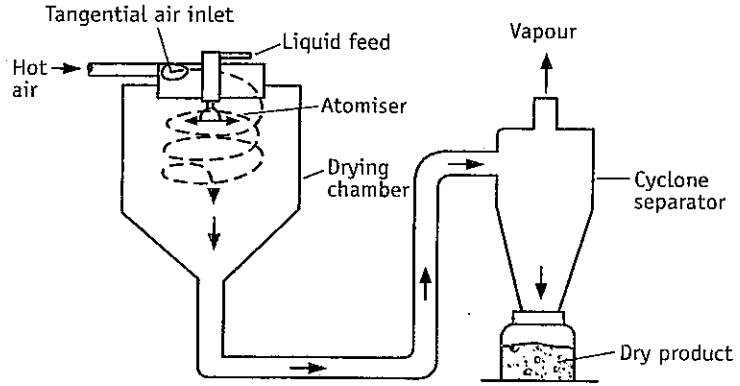


Figure 8-7. Spray dryer.

Working : Drying of the material in spray dryer involves 3 stages.

(1) Atomization of the liquid.
(2) Mixing of droplets.
(3) Drying of the liquid droplets.
(4) Recovery of the dried product.

Atomization of the liquid to form liquid droplets : The feed is introduced through the atomizer either by gravity or by using suitable pump to form fine droplets. The properties of the final product depend on the droplet form, hence, the selection of the type of atomizer is important. Atomizer of any type; pneumatic atomizer, pressure nozzle and spinning disc atomizer may be used.

The rate of feed is adjusted in such a way that the droplets should be completely dried before reaching the walls of the drying chamber. At the same time, the product should not be over heated.

Drying of the liquid droplets : Fine droplets are dried in the drying chamber by supplying hot air through the inlet.

The surface of the liquid drop is dried immediately to form a tough shell. Further, the liquid inside must escape by diffusing through the shell at a particular rate. At the same time, heat transfer from outside to inside takes place at a rate greater than liquid diffusion rate. As a result, heat inside mounts up which allows the liquid to evaporate at a faster rate. This tendency of a liquid leads to rise in the internal pressure, which causes the droplets to swell. The shell's thickness decreases where as permeability for vapour increases. If the shell is neither elastic nor permeable, it ruptures and the internal pressure escapes.

The temperature of air is adjusted in such a way that the droplets should be completely dried before reaching the walls of the drying chamber. At the same time, the product should not be over heated.

Recovery of the dried product : Centrifugal force of atomizer drives the droplets to follow helical path. Particles are dried during their journey and finally fall at the conical bottom.

All these processes are completed in a few seconds. Particle size of the final product ranges from 2 to 500 μm. Particle size depends on solid content in the feed, liquid viscosity, feed rate and disc speed. Spray dryers of maximum size have got evaporating capacity up to 2000 kg/h.

Uses : Spray dryers are used compulsorily, if:

(1) the product is a better form than that obtained by any other dryer,

(2) the quantity of the material to be dried is large, and

(3) the product is thermolabile, hygroscopic or undergoes chemical decomposition.

A few products that are dried using spray dryer are:

acacia	citric acid	hormones	soaps
adrenaline	coffee extract	lactose	sodium phosphate
bacitracin	detergents	methyl cellulose	starch
barium sulphate	dextran	milk	sulphur
blood	extracts	pancreatin	vaccines
borax	ferrous sulphate	penicillin	vitamins
boric acid	fruit juices	pepsin	yeast
calcium sulphate	gelatin	plasma	
chloramphenicol succinate	hexamine	serum	

Advantages:

(1) Spray drying is a continuous process and drying is very rapid. Drying completes within 3 to 30 seconds.

(2) Labour costs are low as it combines the function of an evaporator, a crystllizer, a dryer, a size reduction unit and a classifier.

(3) By using suitable atomizer, the product of uniform and controllable size can be obtained. Free flowing product of uniform spheres is formed which is very convenient for tabletting process.

(4) Fine droplets formed provide large surface area for heat and mass transfer. Product shows excellent solubility.

(5) Either the solution or suspension or thin paste can be dried in one step to get the final product ready for package.

(6) It is suitable for the drying of sterile products.

(7) Reconstituted product appears more or less similar to the fresh material.

(8) Globules of an emulsion can be dried with the dispersed phase inside and layer of the continuous phase outside. On reconstitution, the emulsion will be formed.

Disadvantages:

(1) Spray dryer is very bulky (height of 25.0 m and diameter of 9.0 m). The capital and running costs are high. If the scale of operation is high, then the method becomes the cheapest.

(2) Such a huge equipment is not always easy to operate.

(3) The thermal efficiency is low, as much heat is lost in the discharged gases.

Variants:

(1) Spray dryer can be constructed in such a way as to suit sterile products.

(2) It can be operated under closed conditions to recover solvents.

(3) It can be operated under oxygen free environment.

(4) It can be constructed in such a way that the flow of liquid and gas may be co-current, counter current or a combination of both in the same unit.

(5) The same equipment can be used for spray congealing.

(6) It is useful for encapsulation (coating) of solid and liquid particles.

Fluidised Bed Dryer (FBD)

Principle : In fluidised bed dryer, hot air (gas) is passed at high pressure through a perforated bottom of the container containing granules to be dried. The granules are lifted from the bottom and suspended in the stream of air. This condition is called *fluidized state*. The hot gas is surrounding every granule to completely dry them. Thus, materials or granules are uniformly dried.

Construction : Two types of bed dryers are available, vertical fluid bed dryer and horizontal fluid bed dryer.

The construction of a vertical fluidised bed dryer is shown in Figure 8-8. The dryer is made up of stainless steel or plastic. A detachable bowl is placed at the bottom of the dryer, which is used for charging and discharging. The bowl has a perforated bottom with a wire mesh support for placing materials to be dried. A fan is mounted in the upper part for circulating hot air. Fresh air inlet, prefilter and heat exchanger are connected serially to heat the air to the required temperatures. The temperature of hot air and exit air are monitored. Bag filters are placed above the drying bowl for the recovery of fines.

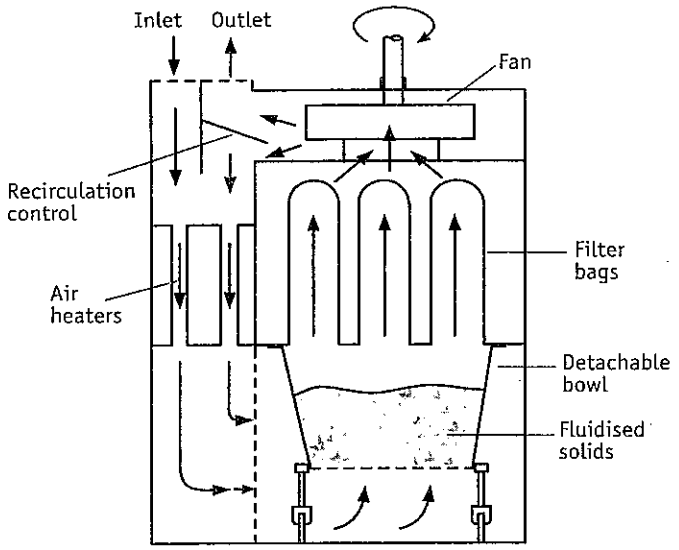


Figure 8-8. Fluidised bed dryer.

Working : The wet granules to be dried are placed in the detachable bowl on the top of retaining screen. The bowl is pushed into the dryer. Fresh air is allowed to pass through a prefilter, which subsequently gets heated by passing through a heat exchanger. The hot air flows through the bottom of the bowl. Simultaneously fan is allowed to rotate. The air velocity is gradually increased.

When the velocity of the air is greater than settling velocity of granules, the granules remain partially suspended in the gas stream. After some time, a point of pressure is reached at which frictional drag on the particles is equal to the force of gravity. The granules rise in the container because of high velocity gas (1.5 to 7.5 metres per minute) and later fall back in a random boiling motion. This condition is said to be *fluidised state*. The gas surrounds every granule to completely dry them. The air leaves the dryer by passing through the bag filter. The entrained particles remain adhered to the inside surface of the bags. Periodically the bags are shaken to remove the entrained particles.

Intense mixing between granules and hot gas provides uniform conditions of temperature, composition and particle size distribution. Drying is achieved at constant rate and falling rate period is very short. Any attempt to increase the air velocity may result in entrainment.

The residence time for drying is about 40 minutes. The drying rate is 10 to 20 times higher than those obtained during tray dryer. The process parameters are established experimentally.

- Maximum, minimum, and optimal air velocities.
- Air temperature,
- Drying time,
- Tendency to cake and channel.

The material is left for some time in the dryer for reaching ambient temperature. The bowl is taken out for discharging. The end product is free flowing.

Uses : Fluidised bed dryer is popularly used for drying of granules in the production of tablets. Fluidised bed dryer can be used for three operations such as mixing, granulation and drying. It is modified for coating of granules.

Advantages:

(1) Fluidised bed dryer requires less time to complete drying, i.e. 20 to 40 min compared to 24 h of tray dryer. Handling time is also short. It is 15 times faster than the tray dryer.
(2) It is available in different sizes with the drying capacity ranging from 5 to 200 kg/h.
(3) The drying containers are mobile, making handling simple and reducing labour costs.
(4) The thermal efficiency is 2 to 6 times than tray dryer.
(5) It is also used for mixing the ingredients and its mixing efficiency is also high.
(6) Hot spots are not observed in the dryer, because of its excellent mixing and drying capacities.
(7) Higher drying temperatures can be used that are not possible in tray dryer and truck dryer.
(8) It facilitates the drying of thermolabile substances, since the contact time for drying is short.
(9) It can be used either as batch type or continuous type.
(10) It has a high output from a small floor space.
(11) The free movement of individual particles eliminates the risk of soluble material migrating as may occur in static beds.

Disadvantages : Many organic powders develop electrostatic charges during drying. To avoid this, efficient electrical earthing of the dryer is essential. The turbulence of the fluidised state of granules may cause attrition of some materials resulting in the production of fines. But using a suitable binding agent this problem can be solved. Fine particles may become entrained and must be collected by bag filters.

Variants : *Plug flow dryer* : It is a rectangular fluid bed dryer having different compartments for fluidisation. The material is made to move from

inlet through different compartments to outlet. Different drying conditions can be maintained in the compartments. Often the last compartment is fluidised with cold gas to cool the solids before discharge.

Vacuum Dryer

Principle : In vacuum dryer, material is dried by the application of vacuum. When vacuum is created, the pressure is lowered so that water boils at a lower temperature. Hence, water evaporates faster. The heat transfer becomes efficient, i.e. rate of drying enhances substantially.

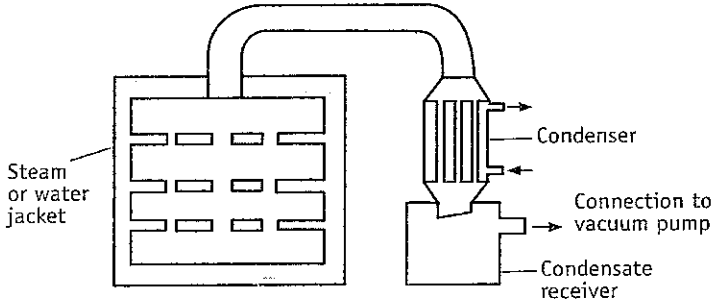


Figure 8-9. Vacuum dryer.

Construction : The construction of a vacuum dryer is shown in Figure 8-9. It is made of a cast iron heavy-jacketed vessel. It is so strong that it can withstand high vacuum within the oven and steam pressure in the jacket. The enclosed space (approximately 1.5 metre cube) is divided into a number of portions by means of 20 hollow shelves, which are part of the jacket. These shelves provide larger surface area (about 45 to 50 m^2) for conduction of heat. Over the shelves, metal trays are placed for keeping the material. The oven door can be locked tightly to give an air tight seal. The oven is connected to a vacuum pump (blowers or steam jets). Vacuum levels range from just under ambient to 20 mgHg by placing condenser in between.

Working : The material to be dried is spread on trays. The trays are placed on the shelves. Door is closed firmly. Pressure is decreased up to 30 to 60 kPa by means of a vacuum pump. Door is closed firmly. Steam or hot air is supplied into the hollow space of jacket and shelves. Heat transfer by conduction takes place. At this vacuum, evaporation of water from the material takes place at 25-30 °C, on account of lowering of boiling point. Drying times are longer, usually of the order of 12 to 48 h. Water vapour passes into the condenser where condensation takes place.

At the end of the drying, vacuum line is disconnected. The material is collected from the trays.

Uses : Vacuum dryer can be used for drying of the following:

(1) Heat sensitive materials, which undergo decomposition.
(2) Dusty and hygroscopic materials.
(3) Drugs containing toxic solvents. These can be separated into closed containers.
(4) Feed containing valuable solvents. These are recovered by condensation.
(5) Drugs which are required as porous end products.
(6) Friable dry extracts.

Advantages:

(1) Vacuum dryer provides large surface area for heat transfer.
(2) Handling of the material, trays and equipment is easy.
(3) It is easy for switching over to the next materials.
(4) Hot water of desired temperatures can be supplied. Electrically heated hollow shelves can be used.
(5) Exclusion of oxygen environment is possible.
(6) Vacuum permits the removal of residual solvent to the extremely low levels.
(7) When low product temperature is desirable, then vacuum drying is cost affective.

Disadvantages:

(1) In vacuum dryer, heat transfer coefficients are low.
(2) It has a limited capacity and used for batch process.
(3) It is more expensive than tray dryer. Labour and running costs are also high. Vacuum connection and accessories are required which adds to the cost.
(4) Sometimes, there is a danger of over heating as the material is in contact with steam heated surface for longer period.

Variants : Double cone tumbling dryer is an alternative to tray dryer, as the drying time is reduced. For drying of granules, the time is 2 to 3.5 h. Vacuum can be applied and hence it is an alternative to the vacuum dryer. Heat is supplied to the charge by contact with the heated shell. Operations such as mixing, granulation and drying can be done in the same equipment.

Freeze Dryer

Freeze drying is also known as *lyophilization*, i.e. system is made solvent loving for removing the same.

Principle : In freeze drying, water is removed from the frozen state by *sublimation*, i.e. direct change of water from solid into vapour without conversion to a liquid phase. Solid-liquid-vapour equilibrium phase diagram of water is useful to decide the experimental conditions. The drying is achieved by subjecting the material to temperature and pressures below the triple point (in practice, below eutectic temperature is essential). Under these conditions, any heat transferred is used as latent heat and ice sublimes directly into vapour state. The water vapour is removed from the system by condensation in a cold trap maintained at a temperature lower than the frozen material.

Construction : The construction of a freeze dryer is shown in Figure 8-10. It consists of:

(1) Drying chamber in which trays are loaded.
(2) Heat supply in the form of radiation source, heating coils.
(3) Vapour condensing or adsorption system.
(4) Vacuum pump or steam ejector or both.

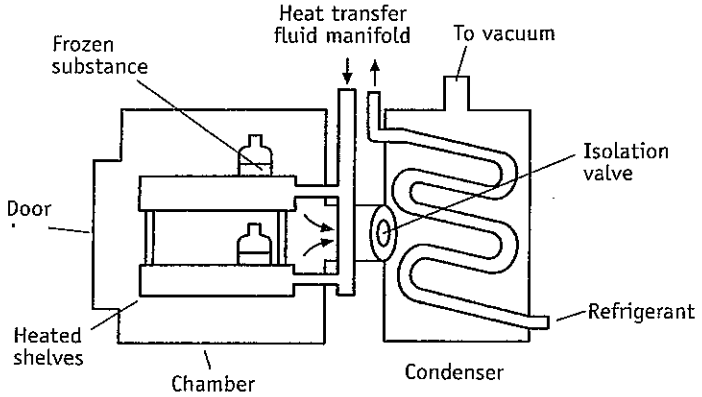


Figure 8-10. Schematic diagram of freeze dryer.

The chamber for vacuum drying is generally designed for batch operation. It consists of shelves for keeping the material. The distance between subliming surface and condenser must be less than the mean path of molecules. This increases the rate of drying. The condenser consists of a relatively large surface cooled by solid carbon dioxide slurred with acetone or ethanol. The temperature of the condenser must be much lower than the evaporating surface of frozen substance. In order to maintain this condition, the condenser surface is cleaned repeatedly.

Working : The working of freeze dryer consists of the following steps.

(1) Preparation and pretreatment
(2) Prefreezing to solidify water

(3) Primary drying (sublimation of ice under vacuum)
(4) Secondary drying (removal of residual moisture under high vacuum)
(5) Packing

Preparation and pretreatment : The volume of solution introduced into the container is limited by its capacity. Satisfactory freeze drying beyond a certain limit of depth of liquid is not possible. Therefore pretreatment is essential. The solution is pre-concentrated under normal vacuum tray drying. This reduces the actual drying by 8 to 10 times. The final product becomes more porous. Liquid or solid desiccants are also used for this purpose.

Prefreezing to solidify water : Vials, ampoules or bottles in which the aqueous solution is packed are frozen in cold shelves (about –50 °C). During this stage, cabinet is maintained at low temperature and atmospheric pressure. The normal cooling rate is about 1 to 3 K/min so that large ice crystals with relatively large holes are formed on sublimation of ice. This is also responsible for giving a porous product.

Primary drying (sublimation of ice under vacuum) : In this step, the material to be dried is spread as much large surface as possible for sublimation. The temperature and pressure should be below the triple point of water, i.e. 0.0098 °C and 0.533 kPa, (4.58 mmHg) for the sublimation, when water alone is present.

When a solution of solid is dried, the depression of freezing point of water occurs. Hence, it is essential that the temperature be brought below the eutectic point. The pressure and temperature at which the frozen solid vaporises without conversion to a liquid is referred to as the *eutectic point*. Depending on the drug substance dissolved in water, the eutectic point is determined. The usual range is from –10 °C to 30 °C. The condition of 1 to 8 °C below eutectic point is sufficient.

Vacuum is applied to the tune of about 3 mmHg (0.4 kPa) on the frozen sample. The temperature is linearly increased to about 30 °C in a span of 2 h.

Heat (about 2900 kJ/kg) is supplied which transfers as latent heat and ice sublimes directly into vapour state. The heat controls the movements of ice layer inwards. It has to be controlled in such a manner so as to get highest possible water vapour at ice surface without melting the material. As soon as vapour molecules are formed, these are removed. The overall driving force is the temperature difference (also vapour pressure difference) between evaporating surface and condenser.

As the drying proceeds, thickness of the frozen layer decreases and the thickness of partially dried solids increases. Primary drying stage removes

easily removable moisture. During this stage, about 98 to 99 % water is removed. Still traces of moisture is present in the sample.

Secondary drying (Removal of residual moisture under high vacuum): During this stage, traces of moisture is removed. The temperature of the solid is raised to as high as 50 to 60 °C, but pressure is lowered below that is used in primary drying (50 mmHg). The rate of drying is very low and it takes about 10 to 20 h.

Packing : After vacuum is replaced by inert gas, the bottles and vials are closed.

Uses : Freeze dryer is most commonly used in the production of dosage forms, such as injections, solutions and suspensions. It is used for drying of a number of products.

- Blood plasma and its fractionated products.
- Bacterial and viral cultures.
- Human tissue (arteries and corneal tissue).
- Antibiotics and plant extracts.
- Steroids, vitamins and enzymes.

Several other products such as food items (prawns, mushrooms, meat and poultry products), coffee and tea concentrates and citrus fruit juices are dried.

Advantages : The entire operation is carried out well below the freezing point. This offers several advantages.

(1) Thermolabile materials (heat sensitive materials) can be dried.
(2) The product retains its bulk volume. It is porous and uniform. The reconstitution of the material is easy.
(3) Denaturation does not occur.
(4) Migration of salts and other solutes does not take place.
(5) Loss of volatile material is less.
(6) Moisture level can be kept as low as possible without decomposition.
(7) Material can be dried in its final container such as single dose and multiple dose vials.
(8) Sterility can be maintained.
(9) The final product can be stored at ambient temperature, if well sealed by providing inert atmosphere.

Disadvantages:

(1) The product is prone to oxidation, due to high porosity and large surface area. Therefore, the product should be packed in vacuum or using inert gas or in a container impervious to gases.

(2) Equipment and running costs are high.
(3) It is difficult to adopt the method for solutions containing non-aqueous solvents.
(4) The period of drying is high (rarely less than 10 h). Time cannot be shortened.

Infra Red Dryer

Infra red heating is used to dry wet granules. It was discontinued for the following reasons. Infra red radiation is absorbed very quickly and does not penetrate deep into the wet mass. As a result, the surface layer gets dried quickly. Further exposure of the radiation leads to overheating of surface layer rather than drying deeper layers of solids. Such effects may decompose the product. Hence, infrared drying has a serious disadvantage.

Microwave Dryer

Microwave drying is also known as *dielectric drying*. Water or solvent with dissolved salts behaves like a dielectric material.

Principle : In microwave drying, microwave radiation (energy) is passed through the solids to be dried. The material absorbs the radiations and experiences enhanced molecular vibrations, which interact with neighbouring molecules. This results in the generation of heat and the centre of the granule gets heated, water gets vapourized and moves outwards to the surface. The mechanism is diffusion of vapour phase. Hot air is used to rapidly sweep the moisture vapour from the drying chamber. Thus rapid drying is achieved by the theory of pressure gradient principle.

Construction : The industrial microwave dryer is a static bed continuous type (Figure 8-11). Dryer is constructed as stand-alone cabinet. Microwaves are produced by a electronic device known as magnetron. Several such units are used depending on the size of the unit and mass of wet material to be dried. High voltage supply is provided so that large amount of heat is produced. Hence, cooling facility is required to reduce the heat. In many applications, pulsed (on/off) controller is used to prevent the damage of the product from excessive heat generation.

Working : The material to be dried is placed on conveyor belt and allowed to move into the drying chamber. Oscillating electric field of 915 or 2450 MHz is applied. The microwave energy interacts with the polarized molecules and ions of the material. As the field reverses polarity, it relaxes and allows the molecules to return to their random orientation. In this process, the stored potential energy is released as kinetic energy or heat. This interaction of alternating fields with ions causes billiard ball like collisions with unionized molecules. This impact energy is also converted into heat.

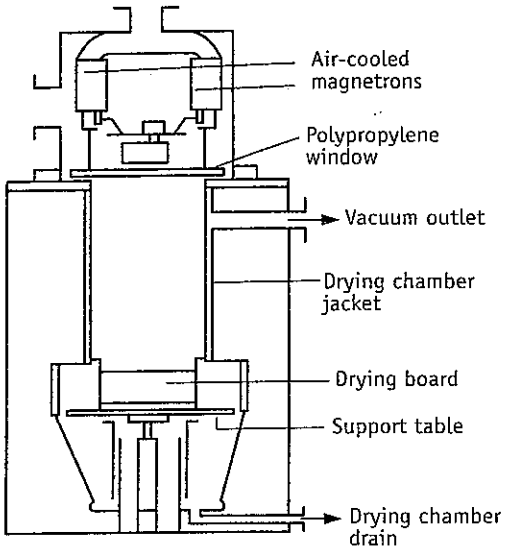


Figure 8-11. Microwave drying equipment.

The heat generated inside the material makes the moisture to get vapourized and subsequently diffused to the surface of the solid. This process is quite rapid compared liquid diffusion (slow). Thus rapid mass transfer is achieved. Completion of drying can be indicated by loss of dielectric constant and its loss of tangent (falling rate period) loss factor. The metal parts and racks do not absorb heat. Hence, conduction and convection mechanisms of heat transfer do not occur. The moisture alone is removed. The microwave type gives drying uniformity and efficiency in energy transfer. The hot air is directed to the powder bed to be dried by way of wave guards. The first order relationship was obtained between drying rate and power input in microwave fluid-bed process.

Uses : Microwave drying can be used for the drying of pharmaceuticals at low ambient temperature. At low pressure (7 to 14. kPa or 1 to 20 mm Hg) and moderate temperature (30 to 40 °C), thermolabile substances can be dried. Examples are: vitamins, enzymes, proteins and flavours.

Advantages:

(1) Microwave treatment can also be used in the last stages of hot air drying, particularly at second falling rate period. Thus last traces of moisture can be removed.

(2) The total drying rate period is reduced by 50 % compared to tray dryer.

(3) Energy utilization is efficient (70 % saving), because the wall of the dryer, the conveyor, the trays donot get heated by microwave radiation.

(4) The generation of dust can be reduced using a single pot process.

(5) Microwave drying technique is superior dryer over conductive drying or jacketed bowl.

(6) It is easily cleanable.

Disadvantages : Initial capital investment is high and a number of accessories are required.

Variants : In some dryers, heat energy also can be passed through jacketed vessel. Moisture can be removed via vacuum or hot air fluidization. Combination dryer with mild vacuum fluidized bed or vibrational capabilities are also used as one pot process.

Comment 8-5. Arrange the dryers in the ascending order of drying times taken for a given material: drum dryer, tray dryer, spray dryer, fluid bed dryer, freeze dryer. Explain.

Comment 8-6. Drying rate is lesser in a static bed dryer compared to a moving bed dryer. True or false. Explain.

Comment 8-7. Tray dryer can be used for drying of thermolabile products. True or false. Explain.

SELECTION OF DRYING EQUIPMENT

Drying requires facilities, equipment, utilities, human labour and time. Thus economic pressure compels the selection of right kind of equipment with less cycling time. The selection of equipment is based on the aspects described in the classification of drying equipment. The nature of drying problem dictates the type of dryer selection. The list containing characteristics and selection of dryer is given in Table 8-3.

(a) Feed Qualities

The feed physical characteristics, such as corrosiveness, toxicity, flammability, particle size, abrasiveness and initial moisture content, are important. The feed may be slurry, coarse, crystalline or sheet type.

- If the material is abrasive, a static bed dryer is preferred over agitated dryer.
- If the material is thermolabile or oxidizable, vacuum dryer is preferred over compartment tray dryer.
- If the solid is wet and available in large quantities, then fluidized bed dryer is preferred.
- If the material is obtained from a biological source and stable in dry state for prolonged period, freeze dryer is preferred.

Quantity of feed to be handled per hour decides the nature of operation, whether continuous or batch type. The process before and after the

drying operations (e.g. filtration, grinding and conveying) are also need to be considered.

TABLE 8-3
Characteristics and Selection of Drying Equipment

Factor relation	*Characteristics*	*Selection of drying equipment*
Material	Slurry	Drum dryer
	Coarse	Tray dryer
	Crystalline	Tray dryer
	Granular	Tray dyer, fluidized bed dryer
	Sheet type	Tray dryer
	Abrasive	Tray dryer
	Thermosensitive	Vacuum dyer
	Hygroscopic type	Spray dryer
	Wet mass	Fluidized bed, tray dryer
	Thin paste	Spray dryer
	Sticky material	Tray dyer
	Biopharmaceuticals	Lyophilizer, microwave dryer
	Friable dry extractive	Vacuum dryer
Product	Porous product	Spray dyer, vacuum dryer
	Fluffy product	lyophilizer
	Free flowing	Spray dryer
	Sterile product	Spray dryer
	Spherical product	Spray dryer
Process	Solvent recovery	Low vacuum dryer
	Toxic solvents	Vacuum dryer
	High dusty	Low vacuum dryer

(b) Product Qualities

Shrinkage, contamination, uniformity or final moisture content, decomposition of products, over-drying, state of subdivision, product temperature and bulk density, are considered, while selecting the equipment for drying.

- If the product is of biological origin, it is required to be reconstituted before use and be identical to that of the original form, then lyophilization is preferred.
- If the product need to be porous and requires quick dissolution, then spray drying is preferred.

- If the product is heat sensitive, then lyophilization technique or vacuum drying is a preferred method.

Type of moisture content (bound, unbound or both), permissible final moisture content, drying temperature and drying type, are a few aspects that need to be considered.

(c) Recovery Problems

Dust recovery and solvent recovery are the aspects to be considered.

- If the solvent is valuable, recovery of solvent is also essential. Therefore, low vacuum dryer is preferred.

(d) Facilities Available at Site

Space, temperature, humidity and cleanliness of air (need for asepsis), available source of heat, (fuel, steam. electric power), permissible noise, vibration, dust or heat loses, source of feed (wet or dry), exhaust gas outlets, etc. are a few aspects to be considered. The scale of operation is an important factor.

(e) Economic Considerations

Value of the material, initial and maintenance costs of the dryer, labour charge, etc. are a few aspects to be considered.

As far as drying operation is concerned, adiabatic dryer are less expensive than non-adiabatic dryers, but have disadvantages of low thermal efficiency and producing high dust. The final choice of a dryer for a particular material depends on the detailed considerations of a variety of factors as mentioned above.

Summary

Drying is a process of removal of small amounts of water or other liquids from a material by the application of heat. In drying, thermal vapourization takes place and the final product becomes dry. Drying is a downstream operation and the next step would be packing (bulk drugs) or further processing (for tablets). Drugs in solid state are stable, easy to handle and possesses improved characteristics, such as uniform size, spherical shape and good flow. Hence, drying is an essential step in the preparation of bulk drug and in some formulations. Drying is achieved by the mechanisms such as diffusion, capillarity, pressure gradient, gravity flow (porous solids) and vaporuization-condensation. Among these, diffusion and capillarity theories are frequently observed and pressure gradient theory is applicable when the heating medium is radiation. The materials undergo sorption/desorption steps and equilibrium relationships are important, which depend on the nature of material and moisture content of the environment in a dryer. Air of constant temperature and humidity is

passed over the wet solid. After a long exposure, equilibrium is reached. The equilibrium moisture content (EMC) is the lowest amount of water that a solid can retain. The drying rate curves are established for each material and the process is tracked for identifying the stages of drying, such as constant drying rate period, first falling drying rate period and second falling drying rate period and finally EMC. The drying of the material is continued until the desired level of moisture content is attained. In tablets production, moisture content of solid will be higher than EMC. In case of preservation and storage, the EMC stage will be reached.

Industrial scale equipment with different designs are developed to meet the varied needs of solid materials. The drying time may vary from a few minutes to several hours. Tray dryer is used in the production of tablets. In this type, the material is loaded into trays and pushed inside a rectangular chamber. Hot air is continuously circulated and the moist air is removed partially. The drying is stopped when the desired moisture content that is suitable for compression is present in the solid. Drying time is longer (5 to 6 h) and thermolabile drugs may decompose. Drum roller dryer is used in the production of antibiotics, glandular extracts, yeast, malt, pigments, etc. The moving metal drum carries the solution, forms a liquid film, which gets heated. Thus moisture is removed (vapourized) and the dried solid is collected. In a spray dryer, the fluid feed liquid is atomized into fine droplets and allowed to enter into moving stream of hot air (in the drying chamber). The fine droplets instantaneously get dried and form spherical particles. This process completes in a few seconds. A fluidized bed dryer (FBD) is used in tablet production and allows the material to dry in 30 to 40 minutes. In FBD, the solids are suspended in the blowing hot air (gas). The hot gas surrounding granules dries the solid rapidly. Vacuum dryer is used if the materials (drugs) are heat sensitive. Vacuum is created in the dryer such that water vapour is removed from the solid at a lower temperature, as the boiling point of liquid is lowered. Freeze dryer (lyophilizer) removes water from the solid by sublimation. For this purpose, low temperature and high vacuum conditions are created such that liquid water in the frozen state directly gets vapourized (below triple point of water). This technique is used for drying blood products, antibiotics, enzymes, and bacterial and viral cultures. Infra red dryer and microwave dryer are a few other techniques. The choice of a dryer depends on the material characteristics of feed, product quality, recovery problems and available facilities including economic considerations. The critical attributes of quality for the drying process are: inlet-outlet temperatures, humidity and time of drying.

Glossary of Symbols

p_{wi} = partial pressure of water vapour at the surface, mPa.
p_{ws} = partial pressure of water vapour in the air, mPa.
N = number of moles of vapour transferred per unit area in unit time.
R = Ideal gas constant, kJ/kmol.K.
T = absolute temperature, K.
k_g = mass transfer coefficient.
M_w = molecular weight of water vapour (18 g/mol).
Q = rate of heat transfer, J/s.
h = heat transfer coefficient, J/s.m^2.K.
A = area of surface, m^2.
T_a = temperature of drying air, K.
T_s = temperature of the surface, K.
k = first order rate constant, h^{-1}.
M_0 = moisture content at initial period, kg (g).
M_t = moisture content (mass) at any time t, kg (g).

QUESTION BANK

Each question carries one mark

Note : Encircle the alphabet which corresponds to the single best response.

1. Drying is essential after one of the following unit operations.
   A. Crystallisation B. Evaporation
   C. Mixing D. Size reduction
2. For fixing the effective drying conditions, which processing factor is essential?
   A. Height B. Humidity
   C. Pressure D. Velocity of air flow
3. At a given temperature and humidity, if the moisture content of a material is greater than equilibrium moisture content, then the following process takes place.
   A. Absorption B. Adsorption
   C. Desorption D. Sorption
4. Fluidised bed dryer has one of the following advantages?
   A. Attrition is not observed
   B. Entire material is continuously exposed to heat source
   C. Fluffy mass is formed
   D. Humidity can be increased
5. Which one of the following dryers is known as lyophiliser?
   A. Fluidised bed dryer B. Freeze dryer
   C. Spray dryer D. Vacuum dryer

6. Talc has equilibrium moisture content (EMC) of practically
   A. high
   B. one
   C. variable
   D. zero
7. Which equipment is used for drying of methyl cellulose?
   A. Drum dryer
   B. Spray dryer
   C. Tray dryer
   D. Vacuum dryer
8. Migration of salts and solutes does NOT occur in one of the following equipment for drying.
   A. Freeze dryer
   B. Spray dryer
   C. Tray dryer
   D. Vacuum dryer
9. Which one of the following types of product is having equilibrium moisture content (EMC) of practically zero?
   A. Non-porous and insoluble
   B. Non-porous and soluble
   C. Porous and insoluble
   D. Porous and soluble
10. Which product is NOT dried by spray dryer?
    A. Bacterial and viral cultures
    B. Fruit juice
    C. Lactose
    D. Serum
11. Hot spots are formed during one of the following periods?
    A. Constant rate period
    B. First falling period
    C. Initial readjustment period
    D. Second falling period
12. Drying process takes long time in one of the following equipment.
    A. Drum dryer
    B. Fluidised bed dryer
    C. Spray dryer
    D. Tray dryer
13. The product becomes porous, when the following equipment for drying is used.
    A. Drum dryer
    B. Fluidised bed dryer
    C. Spray dryer
    D. Tray dryer
14. Thermolabile substances CANNOT be dried using one the following equipment.
    A. Drum dryer
    B. Lyophilizer
    C. Spray dryer
    D. Tray dryer
15. Drying is different from evaporation in one of the following ways.
    A. Liquid removed is low
    B. Temperature applied is high
    C. Quantity of product formed is high
    D. Time required is less
16. In drying process, the final product is in the form of:
    A. slurry
    B. solid
    C. solution
    D. solvent concentrate

17. Which condition is highly critical attribute for drying operation?
    A. Moisture
    B. Pressure
    C. Temperature
    D. Volume
18. Which one of these is non-thermal drying?
    A. Fluidised bed drying
    B. Microwave drying
    C. Spray drying
    D. Vacuum drying
19. Eutectic point is an important factor for one of the following drying processes?
    A. Drum drying
    B. Fluidised bed drying
    C. Freeze drying
    D. Tray drying
20. High vacuum is applied in one of the following drying processes?
    A. Drum drying
    B. Freeze drying
    C. Spray drying
    D. Tray drying
21. Low temperature drying is obtained in one the following drying processes?
    A. Drum drying
    B. Fluidised bed drying
    C. Lyophilization
    D. Tray drying
22. Fluidised bed dryer can be utilised for the following operations.
    A. Drying
    B. Mixing and granulation
    C. Mixing, granulation and drying
    D. Mixing, granulation, coating and drying
23. Attrition is a major disadvantage with one of the following.
    A. Fluidised bed drying
    B. Revolving drum drying
    C. Spray drying
    D. Tray drying
24. In fluidised bed drying, removal of moisture involves one the following mechanisms.
    A. High amount of diffusion
    B. High capillary action
    C. High interfacial contact
    D. High osmotic pressure
25. Drying takes place when moisture content in the air is:
    A. higher than equilibrium moisture content (EMC)
    B. higher than total moisture content
    C. lower than critical moisture content
    D. lower than the EMC
26. Bone dry product means:
    A. granular form of bones
    B. powder from bones
    C. product with bound moisture
    D. product with no moisture
27. Plug flow dryer is a variant of:
    A. Vacuum dryer
    B. Fluid bed dryer
    C. Tray dryer
    D. Freeze dryer

28. Which one of the following is an example of pneumatic dryer?
    A. Drum dryer
    B. Fluidised bed dryer
    C. Freeze dryer
    D. Spray dryer
29. In drying curve, initial adjustment period involves one of the following processes.
    A. Surface water is no longer replaced at a rate fast enough from the bulk.
    B. Temperature and rate of drying remains constant.
    C. Temperature increases and subsequently decreases.
    D. Temperature remain constant.
30. 'Boiling bed' term is connected with one of the following dryers.
    A. Drum dryer
    B. Fluidised bed dryer
    C. Spray dryer
    D. Tray dryer
31. In which dryer, final container such as single dose and multi dose vials are dried?
    A. Fluidised bed dryer
    B. Freeze dryer
    C. Tray dryer
    D. Vacuum dryer
32. In a drying process, once the material reaches equilibrium moisture content, the rate of drying proceeds one of the following.
    A. Constant
    B. High
    C. Low
    D. Zero
33. For drying blood plasma the following technique is used.
    A. Fluidised bed drying
    B. Freeze drying
    C. Spray drying
    D. Vacuum drying
34. Choose the equipment that carries out four unit-operations: mixing, granulation, coating and drying.
    A. Fluidised bed dryer
    B. Freeze dryer
    C. Spary dryer
    D. Vacuum dryer
35. Which one of the following is an example of static bed dryer?
    A. Drum dryer
    B. Fluidised bed dryer
    C. Spray dryer
    D. Tray dryer
36. The use of IR dryer is discontinued for one of the following reactions.
    A. Diffusion of moisture is poor
    B. Environment and labor safety is less
    C. Equipment is batch type
    D. Excessive heat is produced
37. In which step of the freeze drying, most of the water is removed during drying?
    A. Prefreezing
    B. Pretreatment
    C. Primary drying
    D. Secondary drying

38. Hollow shelves are included in the design of a vacuum dryer, for providing increased surface area. What is its purpose?
    A. Conduction of heat
    B. Placing material to be dried
    C. Applying vacuum
    D. Removal of moisture
39. In a spray dryer, the particle size is closely controlled by one of the following parts of the dryer.
    A. Atomizer
    B. Cyclone separator
    C. Drying chamber
    D. Fluid bed
40. In a fluidized bed dryer, a prefilter is included for filtering one of the following
    A. Air
    B. Coarse particles
    C. Fines
    D. Moisture
41. Spray drying and freeze drying differ predominantly in one of the following.
    A. Decreasing the drying time
    B. Improving the dissolution
    C. Decreasing the bulk density
    D. Protecting from degradation
42. Identify the limitation of the freeze drying.
    A. Decreasing the solubility
    B. Increasing the potential for oxidation
    C. Increasing the product stability
    D. Making the product hygroscopic
43. One of the following precautions is taken in handling fluid bed drying.
    A. Allowing conduction for drying
    B. Causing segregation of particles
    C. Ensuring electrical earthing
    D. Preventing the formation of dust
44. Microwave drying is NOT associated with one of the following.
    A. Attrition and dust formation are not possible
    B. Convention and conduction are heat transfer mechanisms
    C. Radiation is used for heat transfer
    D. Use of vacuum is low
45. During drying, solute migration can be promoted by:
    A. decreasing the viscosity of the granulating fluid
    B. fluidizing the powder bed
    C. increasing the granule size
    D. making a static bed for drying
46. Which one of the following types of dryer produces economy?
    A. Fluidized
    B. Microwave
    C. Tray
    D. Vacuum

47. Identify the dryer which has the least thermal efficiency.
    A. Fluidized bed B. Microwave
    C. Spray D. Tray
48. Beyond the equilibrium moisture content, the drying rate is equal to:
    A. One B. Three
    C. Two D. Zero
49. Which one the following mechanisms operate in a tray dryer?
    A. Fluidized bed drying B. Moving bed drying
    C. Pneumatic drying D. Static bed drying
50. Why is a low flow rate of air maintained in a rotary dryer?
    A. Carry away the evaporated water
    B. Evaporate the water
    C. Promote heat transfer
    D. Support the vacuum
51. How does the heat transfer occur in the indirect heat continuous dyer?
    A. Circulation B. Conduction
    C. Convection D. Radiation
52. Identify the method of introducing the feed into the spray dryer.
    A. Atomizing B. Pouring
    C. Self picking D. Spreading
53. Which is the dryer used in the manufacture of soft gelatin capsules.
    A. Fluid bed dryer B. Microwave dryer
    C. Truck dryer D. Vacuum dryer

Each question carries 2 marks

1. Give suitable dryers.
   (i) Granular free flowing solids
   (ii) Wet bricks before sending to kilns
   (iii) Sticky pastes
   (iv) Food products like Horlicks.
2. Define critical moisture content and equilibrium moisture content.
3. Define bound moisture and free moisture content.
4. Mention the factors affecting constant drying rate.
5. Classify dryers giving suitable examples.
6. List the critical conditions for drying of various substances.
7. Define drying. Give its importance in the formulation of dosage forms.
8. Explain how agitator dryers are useful to dry pasty and sludgy materials.
9. How do you obtain the rate of drying curve for a given drying operation? Give its applications.

10. What is the difference between humidity and moisture?
11. The nonporous solid have low EMC compared to porous solids. Explain.
12. Labour costs are low in a spray dryer compared to other dryers. Why?
13. Suggest a dryer that can be used in oxygen free environment and explain the conditions.
14. Why does the product develop electrostatic charges during drying. How can it be prevented?
15. Why are heat transfer coefficients low in vacuum drying?
16. Suggest a method of drying in which containers (product) can be directly used. Explain the procedure.
17. Suggest a drying method, which permits the handling of product at ambient conditions.
18. Give the equipment which produces overheating during drying with reasons.
19. Which is the dryer used for multiple operations: spray dryer or fluidized bed dryer? Give the operations.
20. For the removal of solvent from solids, drying is a preferred method than filtration or evaporation. True or false. Explain.
21. Why is environment (humidity and temperature) controlled during drying?
22. Suggest a non-thermal method of drying. Which is faster: thermal or non-thermal? Explain.
23. How web bulb and dry bulb temperatures are relevant to the drying operation? Explain.
24. Suggest a suitable modification of batch type tray dryer to a continuous dryer.
25. Suggest a suitable modification in a drum dryer of indirect heating can function for direct heating.
26. Is it necessary to use always air in a spray dryer? Explain.
27. What are the advantages of vacuum dryer over tray dryer? Explain.
28. Why is vacuum avoided in microwave drying of granules?
29. What is meant by pressure gradient in tray dryer? How is it achieved?

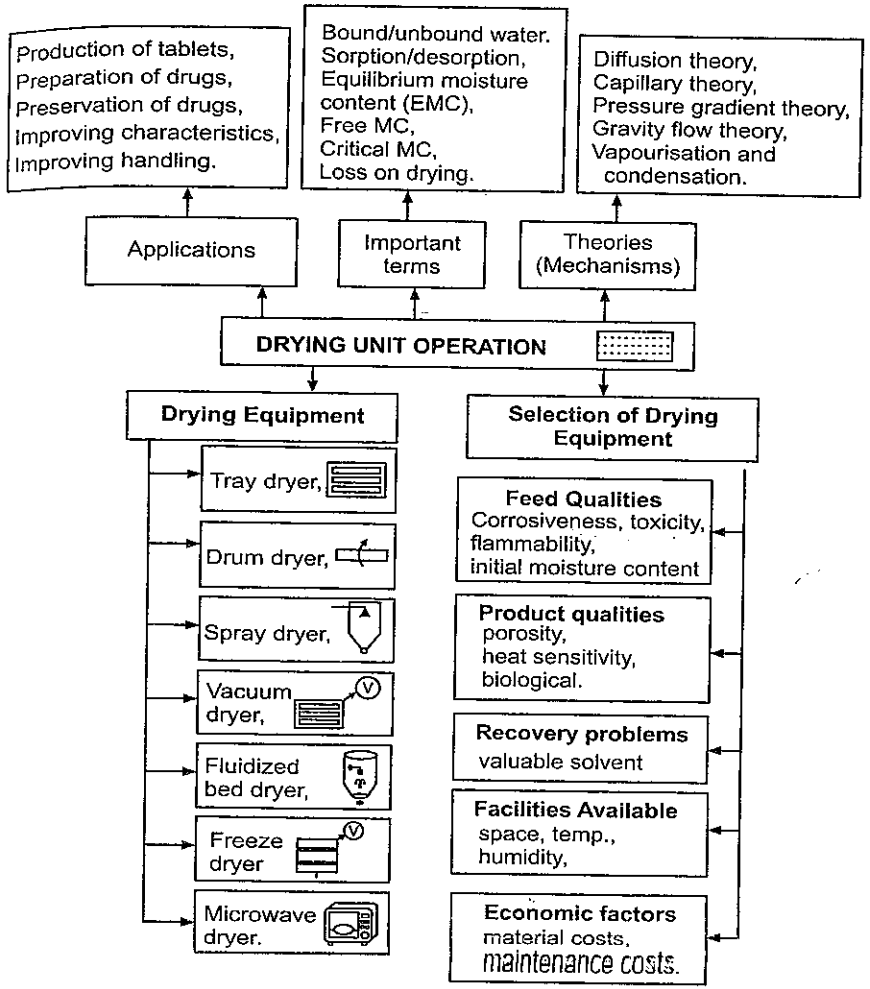
Each question carries 5 marks

1. Recommend a suitable dryer for drying the following substances and substantiate your answer with at least two reasons.
   (A) Liver extracts (B) Granular solids
   (C) Pasty materials (D) Granules of heat sensitive drugs
   (E) Vitamin B complex granules (F) Colloidal solution
2. Describe the drying rate curve for a nonporous granular solid.
3. Describe the principle with the help of a labeled diagram of fluidised bed dryer.

4. List the pharmaceutical applications of freeze drying process. Give salient features of the process.
5. Describe the construction and working of a fluidized bed dryer.
6. Explain the principle of spray drying with suitable labeled diagram.
7. Describe the drying rate curve. Explain its applications.
8. Explain the principle and working of drum dryer.
9. Compare spray drying with drying in a vacuum shell dryer.
10. Explain the factors to be considered in the selection of a suitable dryer.
11. Explain the operation and applications of fluidised bed dryer.
12. Describe the function of drum dryer and its uses.
13. Describe the rate of drying curve for a crude fibrous drug.
14. Explain the principle of freeze drying. What are its applications in pharmacy?
15. Compare the operations of spray dryer and tray dryer.
16. Describe the concept of spray dryer. What are its advantages? Compare the spray drying with other methods of drying.

Each question carries 10 marks

1. Explain the construction and operational details of freeze dryer. Describe its applications in pharmacy.
2. Describe the concept of spray drying. Describe the specific advantages of spray dried product over drum dried material. Also list the pharmaceutical applications.
3. How do you classify dryers? Describe in detail the constant rate and falling rate periods. Add a note on critical moisture content.
4. For drying of milk, we can use either drum dryers or spray dryers. Which dryer will you prefer and why? Discuss drum dryers in detail.
5. Discuss the construction, working, advantages and disadvantages of spray dryer.
6. Explain the theory behind drying and rate of drying with suitable graphs.



MINDMAP OF DRYING UNIT OPERATION

CHAPTER 9

Mixing

Section I : Mixing of Solids
Section II : Mixing of Liquids
Section III : Mixing of Immiscible Liquids
Section IV : Mixing of Semisolids

Section I—MIXING OF SOLIDS

Interparticle Interactions-Segregation
Mechanism of Mixing in Solids
Mixing Process—Steps
Degree of Mixing and Statistical Evaluation
Factors Influencing Mixing
Classification of Equipment for Solids Mixing Equipment
Selection of Solid Mixing Equipment

LEARNING OBJECTIVES

After reading this chapter, the reader should be able to:

- Understanding the principles of solid-solid mixing with applications.
- Explain the steps involved in mixing process.
- Describe mechanisms of mixing, degree of mixing and statistical evaluation.
- Assess the factors influencing solid-solid mixing.
- Describe the designs of industrial scale solid-solid mixing equipment along with working and uses.

Mixing is defined as a process that tends to result in a randomization of dissimilar particles within a system.

Mixing is an operation in which two or more ingredients in separate or roughly mixed condition are treated so that each particle of any one ingredient is adjacent to a particle of each of the other ingredients as nearly as possible.

The term *mix* means to put together in one mass or assemblage with more or less thorough diffusion of the constituent elements among one another. The term *blending* means to mix smoothly and inseparably together. During blending a minimum energy is imparted to the bed. These terms are commonly used interchangeably in the industry. Some of the mixing operations in the dispensing practice are spatulation, trituration, tumbling and geometric dilution. However, industrial pharmaceutical mixing involves large-scale equipment. A major complication in the intimate mixing of particles is the segregation of particulate solids that results from gravitational effect on the agitated bed. Mixing can also be achieved by milling and kneading.

The diverse characteristics of particles, such as size, shape, volume, surface area, density, porosity, flow and charge, contribute to the solid mixing. It is difficult to predict the inter-particle interactions, particularly in solids. Therefore, some empirical correlations are possible. In practice, optimum mixing is considered satisfactory. Depending on their flow properties, solids are divided into two classes; cohesive and noncohesive. *Noncohesive materials* such as grain, dry sand and plastic chips readily flow out of a bin or silo. *Cohesive materials* such as wet clay are characterised by their resistance to flow through openings of the containers.

There are significant differences between solid mixing and liquid mixing. These are given below.

Liquid mixing	*Solid mixing*
Flow currents are responsible for transporting unmixed material to the mixing zone adjacent to impeller.	Flow currents are not possible.
Truly homogeneous liquid phase can be observed.	Product often consists of two or more easily identifiable phases.
Small sample size is sufficient to study degree of mixing.	Large sample size is required.
Mixing requires low power.	Mixing requires high power.

Applications

Mixing is one of the most common pharmaceutical operations. It is involved in the preparation of many types of formulations. Mixing is also an intermediate stage in the production of several dosage forms.

- Wet mixing in the granulation step in the production of tablets and capsules.
- Dry mixing of several ingredients ready for direct compression as in tablets.

- Dry blending of powders in capsules, dry syrups and compound powders (insufflations).
- Production of pellets for capsules.

In the manufacture of tablets, normally a number of additives are added. Therefore mixing of powders becomes an essential part of the process. When the dose of the active substance is high (e.g. paracetamol tablets) mixing is not a problem. But in case of potent drugs and low dose drugs, high amounts of adjuvants (e.g. lactose) are added. Therefore, mixing is considered as a critical factor. Otherwise, content uniformity of tablets does not confirm to the pharmacopœial specifications. Similarly weight variation increases.

Mixing of cohesive materials is even more difficult due to formation of aggregates and lumps. Wet mixing is also encountered in pharmacy as an individual operation or as a subsequent step after dry blending. In several situations, these operations are carried out in a vessel and by some mixing element. Hence, this section describes some aspects of theoretical considerations and equipment for dry as well as wet mixing.

Comment 9-1. Differentiate mixing and agitation.
Comment 9-2. What is the ideal proportion of powders chosen for effective mixing?

INTERPARTICLE INTERACTIONS — SEGREGATION

The particle characteristics such as size, size distribution, shape and surface influence the interparticle interactions in a powder bed.

Inertial Forces

Inertial forces tend to hold neighbouring particles in a fixed relative position. These are van der Waals, electrostatic and surface forces. A special mention of surface forces is relevant.

Surface (or interface) forces : The cohesive forces prevent intimate mixing owing to interaction of their surfaces (or interfaces). Frictional forces also resist the movement of particles so that they tend to form lumps. These depend on surface area, surface roughness, surface polarity, surface charge and adsorbed substances such as moisture. During mixing, the particles develop surface charges. Surface charges produce particle-particle repulsions, which make random mixing impossible. For effective mixing, surface to surface interactions should be minimal, which can be achieved by surface treatment.

Segregation occurs due to the following reasons.

(1) Poor flow properties of the powder bed inside a blender.
(2) Wide differences in particle sizes in a dry mixture.
(3) Differences in the mobilities of individual ingredients.

(4) Differences in particle density and shape to a lesser extent.
(5) Transporting stage, pouring the powder from one container to another (hopper or drums), or emptying the container.
(6) Dusting stage, fine particles become air borne and separate from the bulk of the powder.

Segregation may occur even after the mixing.

Gravitational Forces

Gravitational forces tend to improve the movement of two adjacent particles or groups of particles. Tumbling action promotes the inter-particulate movement due to gravitational forces.

Motion of particles can result from direct contact with the mixer surface or/and from contact with one another. These processes accelerate the movement of translational and rotational modes of single particle or groups of particles. When particle-particle collisions occur, exchange (transfer) of momentum is achieved. Continuous exchange or distribution of momentum between translational and rotational modes is necessary for effective mixing. The efficiency of momentum transfer depends on:

(1) Elasticity of the collisions—If collisions are elastic, effective transfer of momentum does not take place. The loss due to inelasticity should be minimal.
(2) Coefficient of friction—Particles with high coefficient of friction will be likely to exchange rotational momentum more readily.
(3) Surface area of contact—The larger the surface area of contact, greater the exchange of momentum.
(4) Surface roughness—The surface 'roughness' of the particles involved in collisions determines the distribution of the transferred momentum between translational and rotational modes.
(5) Centrifugal forces—These act on rotating aggregates to break them into smaller units and aid in mixing process.

MECHANISMS OF MIXING IN SOLIDS

Segregation of particles occurs due to a number of reasons. Mixing can prevent it. The principal mechanisms in solid-solid mixing are:

Convective Mixing

Convective mixing is achieved by the inversion of the powder bed using blades or paddles or screw element.

A large mass of material moves from one part to another. Convective mixing is referred to as *macromixing*. This is observed in ribbon and planetary mixers (paddle or plow).

Shear Mixing

In this type, the forces of attraction are broken down so that each particle moves on its own between regions of different composition and parallel to their surfaces.

In a particulate mass, the forces of attraction are predominating, which make the layers *slip over one another*. Such types of attraction forces are predominant among same type of particles. Shear forces reduce these attractions and reduce the scale of segregation. This is achieved by high intensity mixers (rotor mixers).

Diffusive Mixing

It involves the random motion of particles within the powder bed, thereby particles change their positions relative to one another. This occurs on account of free flowing particles in an expanded bed.

Diffusive mixing occurs at the interfaces of dissimilar regions. Diffusion is sometimes referred to as *micromixing*.

The motion of particles to achieve random distribution assumes that no other factor influences the distribution. Vertical or axial motion is observed as in case of rotational blender, e.g. V cone blender (tumble) and double cone blender. This is rarely the case. Instead, a number of properties of the powders influence the approach to randomness. Flow characteristics of powders largely determine the ease with which the primary particles can be mixed.

MIXING PROCESS — STEPS

In the solid-solid mixing operation four steps are involved. These are:

1. Expansion of the bed of solids.
2. Application of three-dimensional shear forces to the powder bed.
3. Mix long enough to permit true randomization of particles.
4. Maintain randomization (no segregation after mixing).

When dry materials are loaded into a mixer, they form a static bed. This bed expands sufficiently when mixing is initiated. Therefore, there should be enough void space in the mixer after it is charged with the ingredients.

The shear force produces movement of particles. This is accompanied by expansion of powder bed. The stress induces the movement of particles in three directions. This turbulent movement of particles can achieve randomization. If the forces are inadequate, particle agglomerates move together leading to poor mixing.

Mixing is expected to produce random distribution of particles. It depends on the probability that an event happens in a given time. The law of mixing appears to follow a first order.

$$M = A\,(1 - e^{-kt}) \qquad \ldots(1)$$

where M = degree of mixing after time t
t = time, min
A & k = constants

The constants A and k depend on the mixer geometry, physical characteristics of the powders and proportion of the material being mixed.

Initially the rate of mixing is rapid. At a later stage the rate decreases. Since the rate process is first order (asymptotic), perfect mixing is not attainable, i.e. it takes infinite time. Empirically the best mixing time would be 30 to 35 min. Once the desired mixture has been achieved, the process should be stopped.

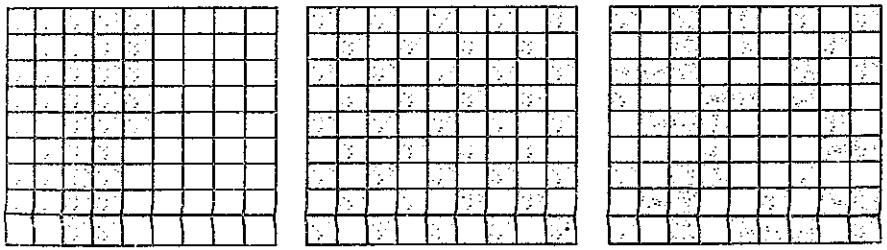
Once mixing is stopped, the blend should exist in static equilibrium. Subsequent handling of the mixture should be so as not to disturb the static equilibrium.

DEGREE OF MIXING AND STATISTICAL EVALUATION

Degree of mixing is also known as *degree of homogeneity*. After mixing, the best possible degree of mixing can be achieved provided each particle moves freely to every spot of the equipment. It requires the movement of particles in three directions. The degree of mixing must be considered for the purpose of economics. Time of mixing should be long enough to obtain an acceptable randomisation.

Ideal Mixing or Perfect Mixing

As illustrated by equation (1), the mixing process will never yield an *ideal or perfect mixture*. Ideal degree of mixing is represented schematically in Figure 9-1a by a chessboard with black and white squares representing two components (equal quantities). It indicates that each particle of one component is lying nearly adjacent to a particle of another component. In practice, degree of mixing is indicated by its standard deviation.



(a) Two components before mixing (b) Perfect mix (c) Randomized mix

Figure 9-1. Types of binary mixtures.

Acceptable Mixing

Since perfect mixing cannot be achieved, other alternatives for obtaining an acceptable mix must be considered.

Random mixing : It is indicated by random distribution of particles as shown in Figure 9-1c. *Random mixing* means same ratio of components in the entire mixture. Artificial randomization in the Figure 9-1c is based on random numbers in statistical tables. However, it should be noted that the use of random motion to achieve random distribution assumes that no other factor influences the distribution. This is rarely the case. Instead a number of properties of the powders being mixed influence this approach to randomness.

Ordered mixing : Ordered mixing is described as the use of mechanical, adhesional and coating forces. Ordered units in the mix should be such that ordered unit will be the smallest possible sample to the mix. It will be nearly identical in composition to all other ordered units in the mix.

Ordered mixing probably yields the closest situation of the perfect mix. This can be achieved by a number of ways.

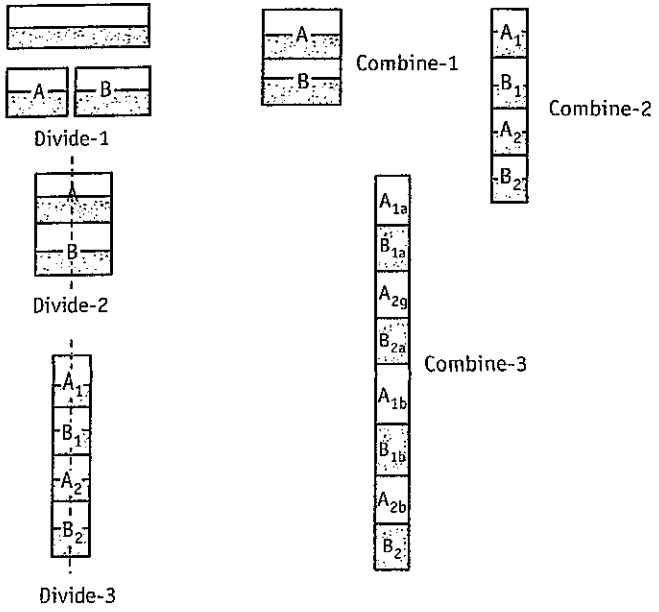


Figure 9-2. Ordered mechanical mixing.

(1) Mechanical means of ordered mixing : The mass of each ingredient is divided and recombined a number of times in the powdered bed (Figure 9-2). The smaller the units, the more uniform the mix. Since no particulate adhesion is present, segregation of the mix easily takes place on further handling.

(2) **Adhesion means of ordered mixing :** These forces of particles may create ordered units of nearly identical composition depending on the process (Figure 9-3a). Partial solubilisation or the use of a binding agent during wet granulation approximates the same effect as shown in Figure 9-3a.

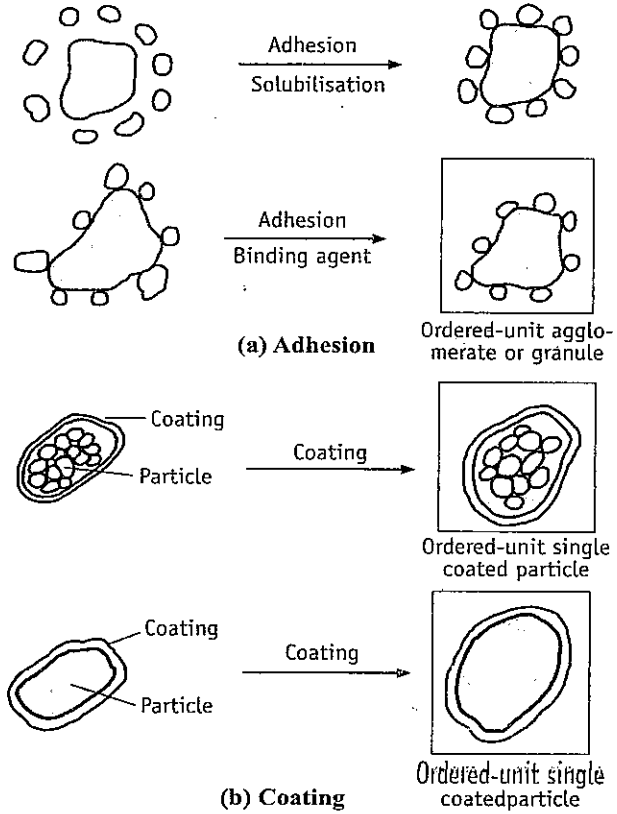


Figure 9-3. Ordered mixing based on the principles of (a) adhesion and (b) coating.

(3) Coating means of ordered mixing : Particles in an assemblage may also be coated with other ingredients to give an ordered mix either as individual or coated particle agglomerates (Figure 9-3b).

Ideally, the degree of mixing begins rapidly up to a particular level and slows down gradually. Uniform degree of mixing can be resulted by continuing mixing for some more time. The practical definition of mixing uniformity is selected to relate as closely as possible to the desired properties of the mix. The sampling technique largely determines the validity and interpretation of the derived mix.

Statistical Parameters

The analysis of samples before and after mixing provides information about the degree of mixing. Solid mixing with some kind of tracer material is used for easy analysis. Some important methods of analysis are the particle size distribution and the assay procedures for different ingredients in the sample.

Arithmetic mean : The mean (assay value or size distribution analysis) value of a group of random samples is a measure of the central tendency of the batch population. The arithmetic mean is expressed as:

$$\text{Arithmetic mean,} \quad \bar{y} = \sum_{i}^{n} \frac{y_i}{n} \qquad ...(2)$$

Taking a number of samples (n), the true mean, y, is estimated. Mean may be attributed to concentration of a component or particle size of a component.

Standard deviation : The spread of dispersion of individual samples is important, because it is impracticable to obtain the same true mean for the same product mix obtained by another lot or by another mixer. Therefore, standard deviation is used. It is expressed as:

$$\text{Standard deviation,} \quad \sigma = \sqrt{\frac{\sum_{i}^{n} (y_i - \bar{y})^2}{(n-1)}} \qquad ...(3)$$

Variance, which is a square term of standard deviation, can also be used for characterisation of powder mix. Standard deviation is applicable for a specific material and a specific mixer. The arithmetic mean and standard deviation are applicable, when the two components are alike in particle size, shape and density. The only distinguishable feature is a neutral property, such as colour.

Mixing of pharmaceutical powders should be continued until the amount of the active drug that is required in a dose is within ± 3 SD units of that found by assay in a representative number of sample doses. To achieve this objective, n should be large. It indicates that the samples are normally distributed around the mean content and 99.7 % of the samples will fall within the limits, $p = 0.5 + 3\sigma$, where p is the proportion of one component. The theoretical deviation depends on the differences in the size, shape and density and these prevent the formation of random mixing.

Relative standard deviation : One may follow the mixing operation in a given process by plotting the standard deviations as a function of time.

The relative standard deviation (RSD) should replace the standard deviation as a measure of sample uniformity, which is expressed as:

$$\text{Percent relative standard deviation (RSD)} = \frac{\text{standard deviation } (\sigma)}{\text{mean } (\bar{y})} \times 100 \qquad ...(4)$$

Equation (4) is useful for comparing the efficiency of two or more mixing operations or different sample sizes or different compositions.

Mixing Indices

The selection of a mixer depends on the mixing index or degree of mixing. The above mentioned statistical parameters are useful for evaluating the mixing indices.

Mixing index involves the comparison of standard deviation of sample of a mixture under study with the estimated standard deviation of a completely random mixture.

Mixing index is expressed by Lacey. Two of them are:

$$\text{Mixing index, } M = \frac{\text{standard deviation of random blend}}{\text{standard deviation of the sample blend}} \times \frac{\sigma_R}{\sigma} \qquad ...(5)$$

$$\text{Mixing index, } M = \frac{\sigma_0 - \sigma}{\sigma_0 - \sigma_R} \qquad ...(6)$$

where σ_0 = standard deviation of unmixed powder.

The ratio will be less than 1. The higher the M value, the greater the homogeneity. Equations (5) and (6) are used to determine homogeneity in a mixture depending on the objectives at hand. The selection of a particular equation is essential when the mechanism of mixing is being investigated. Practical use of results can be achieved by using statistical analysis.

The differences may indicate poor or inadequate sampling, inappropriate mixing operation, improper handling of the powder sample, unsuitability of the mixer, operational conditions, etc.

Before mixing has begun, the material in the mixer exists in two layers, one of which contains no tracer material and one of which is tracer only. Under these conditions, the standard deviation at zero time (σ_0) may be expressed as:

$$\sigma_0 = \sqrt{a\,(1-a)} \qquad ...(7)$$

where a = overall fraction of tracer in the mixture.

Statistical Evaluation

Mixer selection depends on the degree of mixing of the powder in the final product. The procedure involves sampling and analysis. The sequence of steps involved in the evaluation of the degree of mixing or degree of homogeneity is given in the Table 9-1.

TABLE 9-1

Statistical Evaluation Procedure for the Blending or Mixing of Powders

Objectives

1. To compare the efficiency of two or more mixing operations.
2. To compare the efficiency of two or more equipment.
3. To follow the mixing process with time.
4. To optimise processing parameters.
5. To investigate the mechanism of mixing in a given piece of equipment.

Sample size guidelines	(*a*) Random sampling, (*b*) Number of samples
Number of samples	Required — 30; Ideal — 100; Economical sampling — 20 (preferred).
Sample size	approximately a unit dose of the final product.
Sample collection	*a*. At different intervals when the blend is in motion. *b*. After blending is completed (preferred).
Sampling methods	*a*. Scooping *b*. Thief probing (preferred)
Sample utilization	*a*. Returning the sample to the bulk, for example, after completion of particle size analysis (non-destructive evaluation). *b*. Not returning the sample to the bulk, for example, due to solubilisation for assay procedure (destructive method).

Statistical analysis

- Determination of arithmetic mean and standard deviation of the randomly mixed sample (standard).
- Determination of arithmetic mean and standard deviation of the unmixed blend of sample (initial stage).
- Determination of arithmetic mean and standard deviation of the sample after blending (test sample).
- Comparing mean values (sample) with target value (true mean).
- If they are comparable, standard deviation should be calculated (indicates uniformity of the sample). High standard deviation indicates less uniformity.
- Determination of mixing indices.
- Scattering of sample about mean or standard deviation (plot of standard deviation vs. time).
- Accuracy and precision assessments of these estimates.

The objectives have been specified in the Table 9-1. The sampling technique largely determines the validity and interpretation of the derived mix.

Criteria of sampling : While sampling a bed of powder, there should be assurance that the bed is sampled uniformly. It is assumed that the powder bed consists of a number of zones. Within each zone the composition is uniform, but among zones, the composition is different. Therefore, method of sampling is very important. For this purpose, two concepts are important.

Scale of segregation : It is a function of size of the zone. It assumes that zones are having uniform bed, but differing in composition. Good mixing should yield more number of zones with small size. Then the sample reflects the true character of the powder bed.

Intensity of segregation : It is a function of composition differences among zones. Generally the process of mixing tends to reduce the intensity of segregation.

Sample size guidelines : The number of samples required should be not less than 20, preferably 30 and more ideally 100. Analysis of these samples is time consuming and tedious. Therefore, economic considerations suggest 20 samples.

Random sampling is the method of choice for studies. Sample size, in most cases, should approximate the unit dose size of the final product.

Collection of samples : Some golden rules of sampling are:

1. A powder should be sampled when it is in motion.
2. The whole of the stream of powder should be taken for many short increments of time in preference to a part of the stream taken for the whole time.
3. After completion of the mixing also, samples should be taken.

Sometimes, powder sample cannot be sampled from a moving stream, because:

(1) configuration of the mixer – for example the shape of the bowl does not lend itself to dumping.
(2) size of the batch – large volumes are not conducive to routine transfer from the blender to drum or larger collectors.
(3) possibility of mixture segregation biasing the sample.

Therefore, it is always preferable to collect the sample once mixing is completed.

Method of collecting samples : Samples should be collected at selected points or serially as the powder is discharged from the mixer. Two types of sampling methods are adopted.

(1) Scoop sampling of the bulk mixture

(2) Thief probing of the bulk mixture

Scoop sample : This method has some drawbacks. (A) Surface layer sample may represent segregated mixture. (B) Samples cannot be taken from the bottom and middle of the blender or container.

Thief probe : This method has some drawbacks. (i) During sampling, some compaction takes place around the thief. (ii) As the thief is inserted in the powder bed, it carries material from the surface of the mixture down into the mixture.

Thief probe is preferred over the scoop, because samples can be taken from deep within the powder bed and a fair degree of random sampling can be achieved.

Sample utilization : If the method of analysis is non-destructive, for example, particle size analysis, the sample can be returned to the mixture after analysis. If the method is destructive, for example assay, the sample cannot be returned.

Analysis of data : Several statistical parameters and mixing indices are calculated. The comparison of the mean value of the sample under analysis and the target value. If the mean value of the sample under analysis is on or near the target value, calculation of the standard deviation (and or variance) will give an indication of the uniformity of the sample. Other details are given in Table 9-1.

Comment 9-3. Write the differences in the sampling methods of powders: scoop sampling and thief probing.

Comment 9-4. Write the relationship between the efficiency of mixing and the volume of the material filled in the mixer.

FACTORS INFLUENCING MIXING

Particle and powder characteristics influence the mixing process. Aggregation inhibits proper mixing. Therefore, higher shearing forces are applied. Hence, correct mixing of one component does not imply good mixing of other components. Therefore, adding dye to the mixture is often misleading. The dye may not aggregate, but active substance may aggregate.

A single factor can in no way be considered as a unique indication of mixing. However, flow properties of the components is the most important consideration which is again influenced by a number of factors.

Nature of the surface : Rough surface of one of the components does not induce satisfactory mixing. This can be due to the entry of active substance into the pores of the other ingredients. Adding a substance, which

will be adsorbed on rough surfaced particles, can decrease aggregation, e.g. the addition of aerosil (colloidal silicon dioxide) to zinc oxide. Thus, a strongly aggregating zinc oxide becomes a fine dusting powder, which can be mixed easily.

Density of the particles : It is of minor importance. Demixing is accelerated when the density of the smaller particles is higher or when the mixing process is stopped abruptly. This is due to the fact that dense material always moves downward and settles at the bottom.

Particle size : It is easy to mix two powders having approximately the same particle size. The variation of particle size can lead to separation, because the small particles move downward through the spaces between the bigger particles. As the particle size increases, flow properties also increase due to the influence of gravitational force on the size. Beyond a particular point, flow property decreases. The powders with a mean particle size of less than 100 μm are free flowing, which facilitates mixing.

Particle shape : The ideal particle is spherical in shape for the purpose of uniform mixing. The irregular shapes can become interlocked and there are less chances of separation of particles once these are mixed together.

Particle charge : Some particles exert attractive forces due to electrostatic charges on them. This can lead to separation or segregation.

Proportion of materials : The best results can be obtained if two powders are mixed in equal proportion by weight and by volume. If there is a large difference in the proportion of two powders, mixing is always done in the ascending order of their weights.

The fundamental aspects of the particles and powders are discussed in the Textbook of Physical Pharmaceutics-II by C.V.S. Subrahmanyam (Vallabh Prakashan, Delhi).

CLASSIFICATION OF EQUIPMENT FOR SOLIDS MIXING

Based on the flow properties of the powders, appropriate mixer should be selected.

Free flowing solids	– V cone blender
	– Double cone blender
Cohesive solids	– Planetary mixer
	– Sigma blender

Based on the scale of mixing, mixing equipment may be classified as given in Table 9-2.

TABLE 9-2
Classification of Mixing Equipment

S.No.	*Nature of mixer*	*Examples*	*Mechanism of mixing*
1	**Batch type** Small scale	Mortar and pestle	Trituration
2	Tumbling mixers or cylindrical mixers without mixing blade	Double cone blender, V cone mixers without baffles Cube blender	Tumbling action, diffusion
3	Tumbling mixer with a mixing blade	V cone blender with a mixing blade Double cone blender with a mixing blade	Tumbling action shearing with blade and convection
4	Static mixers	Ribbon blender Sigma blender Planetary paddle	Stationary shell and rotating blade, convection and shearing
5	Air mixers or fluidized mixers	Fluidised mixer	Air supported blending, expansion with gases, diffusive and pneumatic
6	**Continuous type** Large scale	Barrel type Zigzag type	Rotating shell with rotating blade, shear and convection

Critical Quality Attributes – Preblending of Solids and Final Blending

The critical quality attributes (CAQs) along with process parameters (PPs) are recorded in Figure 9-4. Preblending of solids is considered for the production of tablets (capsules). The upstream operation may be a size reduction (sizing and/or blending) and the downstream operation is granulation. As per these conditions, the critical attributes are related to content uniformity, as given below.

- Mixing uniformity
- Flow properties
- Bulk/tapped densities
- Assay

The process parameters are: fill volume, speed of mixer and time of mixing. These are controlled during the unit operation and prefixed as standards with limits for given conditions. Production charts can be used for monitoring the parameters. The above are general attributes, but change depending on the mixer type used and the mechanisms of mixing.

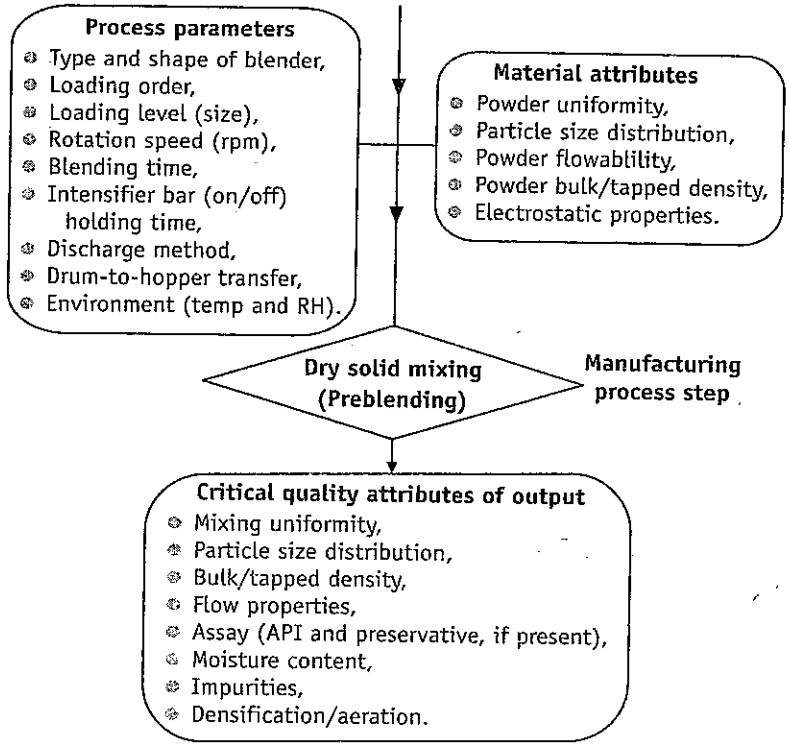


Figure 9-4. Process parameters and critical quality attributes for preblending operation of solids in production of tablets.

Further, solid mixing with lubricant is another important operation, a step before compression (Figure 9-5). For this purpose, a lubricant is added for good flowability and blend uniformity, which are critical. As such the process development remains the same, except including magnesium stearate and monitoring moisture content (for compression). Normally mixing may be an open operation (sigma mixer and planetary mixer) or closed operation (V cone blender and double cone blender). The environment (temperature and relative humidity) are maintained in the production area.

Critical Parameters

The key parameters are:

1. Rotating frequency, proper mixing time
2. Equipment size, mixer volume (fill ratio)
3. Scheduling and surge
4. Segregation

The rpm and time are frequently standardized and quoted. The rotating speed is critical. In addition, the other issues are material handling (feed and discharge).

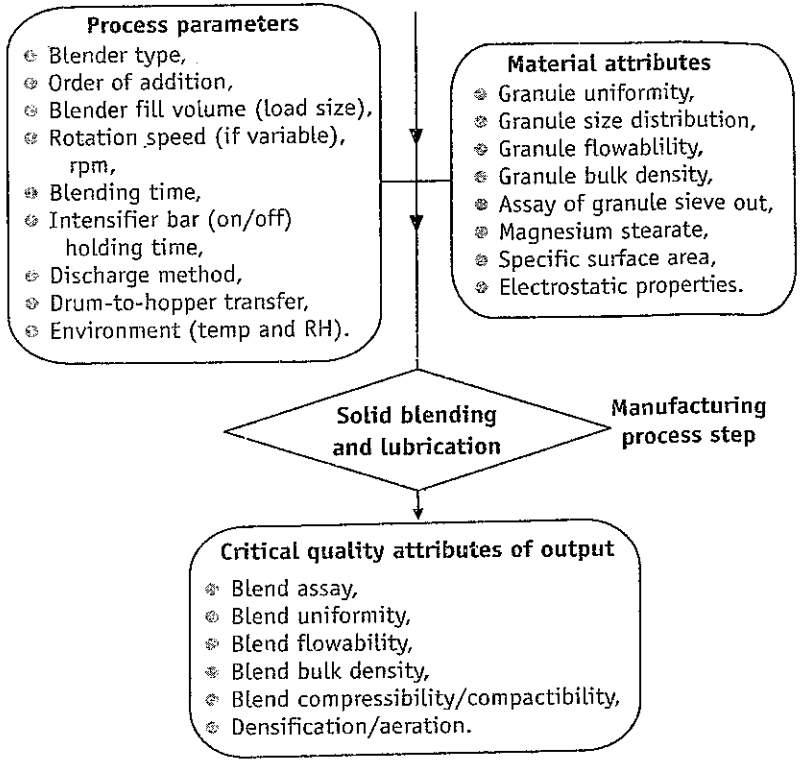


Figure 9-5. Process parameters and critical quality attributes for final blending operation of solids in production of tablets.

Mixing time : Mixing more time is not necessarily better. The optimal mix time must be determined experimentally. It is a tedious procedure and requires several samples for analysis. The scale up parameters such as geometric ratio and keeping Froude number a constant are desirable. Normally the time of mixing is 10-20 min. The kinetic study gives how long to mix and how well to mix (equilibrium). In general, the mixing time will be shorter, the quality is higher and this results in less rework.

Rotation speed : Rotation speed (rpm) must be usually an optimum value. *If the speed is too low, there would be no agitation, but at low* speeds avalanching flow can occur. At high speeds, centrifugal force throws all the material to the perimeter. In both cases, blending is not efficient. Hence, rpm should be optimum. The Froude number is the relevant scaling parameter. Excessive mixing can promote segregation.

Fill volume : Most solid mixers have working volumes equal to 50 % of their total volume. In ribbon or paddle blender, the material is filled to just above its shaft. In tumblers and V-blenders, the material must be only partially filled. If a mixer is overfilled, it is difficult for the solids to move by the agitator and mixing will be poor at best. The scaling parameters for mixing are given in Table 9-3.

TABLE 9-3
Scaling up the Parameters for Mixing

Working capacity, L	*Typical rpm*	*Typical amount, kg*
20-50	25-30	8-30
250	22-28	80-150
500	12-18	200-300
2000	8-12	800-1200

Rotational velocity is the key blending parameter
Rotation tip speed (100 m/min) and momentum (mass x velocity) stay same during scale up
As mass increases, blender rpm decreases.

Scheduling and surge : The mixing process consists of loading directly into a mixer, mixing for the correct time, and then dumping directly into packages or processing further. Normally some type of elevation of work-platform is required so that the material is shifted initially on to the platform and then the mixer is charged. The discharge is collected directly into the storage bags.

Blend uniformity analysis (BUA) : For an acceptable mixing, the variables are identified. In order to set them at optimum levels, blending is evaluated through a set of tests.

EQUIPMENT

A mixer that promotes the randomness in mixing should be selected. It should also prevent the conditions responsible for segregation. Therefore, optimization of operational conditions is critical.

Mixing Equipment—Criteria

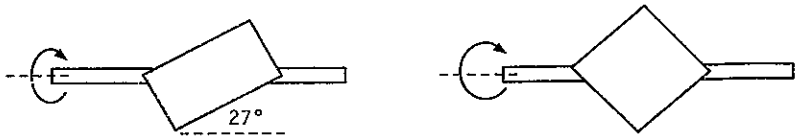
1. The powder bed may expand sufficiently, therefore, equipment should never be filled for more than about 60 % so as to leave sufficient mixing volume.
2. The particles should be subjected to movement in three directions.
3. The shearing force should be sufficient to prevent aggregation. Appropriate mixing mechanism should be selected and allowed to continue for optimum time.

4. There should be no centrifugal effect, so that the powder does not get separated according to their weights.
5. The forces should not cause breakage of the particles, which may bring about demixing due to differences in particle size.
6. The mixing process should be stopped abruptly, because slow or diminishing forces in one direction might cause demixing. Therefore handling of powder blend after mixing is equally important.

Some mixing equipment are discussed below.

Tumblers or Cylindrical Blenders with No Mixing Blade

This is a general class of equipment meant for blending of dry powders. The equipment consists of a container of one of the several geometric forms. The equipment is mounted so that it can be rotated about an axis. It does not have packing glands (seals) round the shaft. Cubes or hexagonal cylinders may be rotated in any axis depending on the manufacture (Figure 9-6). A cylindrical vessel is not suitable for mixing since one-dimensional movement would be obtained.



(a) Cylindrical blender **(b) Cube blender**

Figure 9-6. Tumbler blenders without agitator blade.

Edge of 27 degrees is good for mixing. Special rollers are available on which any vessel can be placed at the optimal condition. These are very handy since the vessel can be used every where in the process. When mixed, cohesive powders tend to ball up and aggregate. Therefore, tumbler type is not suitable.

The efficiency of a tumbling mixer highly depends on the speed of rotation. It should be critical.

(1) Slow rotation – No intense tumbling, no cascade motion. Not enough shear rates is applied.

(2) Rapid rotation – Sufficient centrifugal action to hold the powder to the sides of the mixer, more dusting and segregation of fines is possible.

Therefore, the rate of rotation should be optimal, which depends on the size, shape of the tumbler and the nature of material to be mixed. Common range is 30 to 100 rpm.

Neither cylindrical nor cube mixers are used to a great extent in the industry. For simple blending of dry mixers, V cone and double cone blenders without baffles are used. The tumbling motion is accentuated by means of baffles or simply by virtue of the shape of the container.

Twin Shell Blender or V Cone Blender

The construction of a twin shell blender is shown in Figure 9-7. It is made of either stainless steel or transparent plastic. Smaller models take a charge of 20 kg and rotate at 35 rotations per minute, while larger ones take a charge of about 1 tonne and rotate at 15 rotations per minute. The material is loaded through either of the shell hatches. Emptying of the blend is normally done through an apex port.

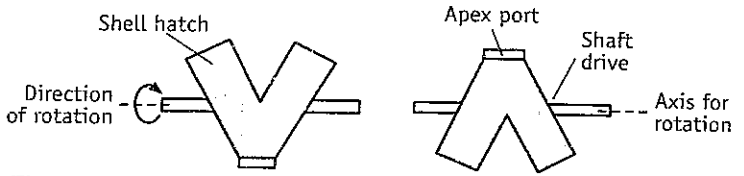


Figure 9-7. V cone blender. Rotating shell hatch without baffles.

The material (to be blended) is loaded approximately 50 to 60 % of its total volume. As the blender rotates, the material undergoes tumbling motion. When the V is inverted, the material splits into two portions. This process of dividing and recombining continuously yields ordered mixing by mechanical means. Tumbler mixer operates primarily by diffusive mixing. Hence these mixes are suitable to materials of free flowing and granular nature and mild forces are sufficient for mixing. The powder mass is converted shock-wise, so that no demixing due to density differences will occur. It is rotated so that the material is alternatively is collected in the bottom of the V.

Blender speed is the key for mixing efficiency. At high speeds, more dusting or segregation of fines is possible, while at low speeds, not enough shear may be applied.

Advantages:

(1) If fragile granules are to be blended, twin shell blender is suitable because of minimum attrition.

(2) They handle large capacities.

(3) Easy to clean, load and unload.

(4) This equipment requires minimum maintenance.

Disadvantages:

(1) Twin shell blender needs high headspace for installation.

(2) It is not suitable for fine particulate system or ingredients of large differences in the particle size distribution, because not enough shear is applied.

(3) If powders are free flowing, serial dilution is required for the addition of low dose active ingredients.

Double Cone Blender

The construction of a double cone blender is shown in Figure 9-8. It is usually charged and discharged through the same port. It is an efficient design for mixing powders of different densities. The rate of rotation should be optimum depending on the size and shape of the tumbler, nature of material to be mixed. Commonly the range is 30 to 100 revolutions per minute. The method remains same as that of the V-cone blender.

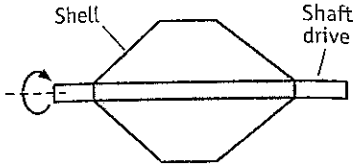


Figure 9-8. Double cone blender. Rotating shell without baffles.

The advantages and disadvantages for double cone blender are same as given in Twin shell blender (or V cone blender).

Tumbling Blenders with Agitator Mixing Blade

The V-cone blender and double cone blender with agitator blade (baffles) are shown in Figures 9-9 and 9-10, respectively. The general construction and working is same as mentioned above. The agitator blade rotates, lifts and distributes the material in an irregular manner. Convective and shear mixing occur as well as some fine-scale diffusive mixing occurs. Agitator blades are added which have several advantages.

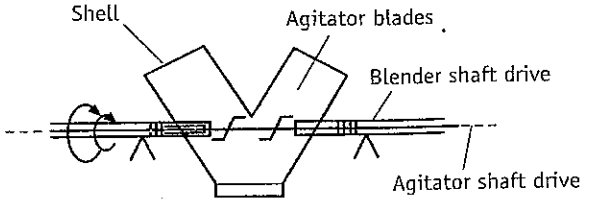


Figure 9-9. V cone blender. Rotating shell with rotating baffles.

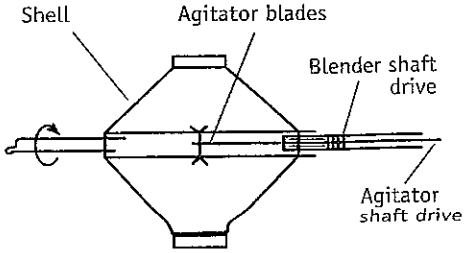


Figure 9-10. Double cone blender. Rotating shell with rotating baffles.

Advantages:

(1) Baffles are useful for both wet and dry mixing.

(2) Wide range of shearing force can be applied with agitator blades permitting the intimate mixing of very fine as well as coarse powders.

(3) Serial dilution is not needed when incorporating low-dose active ingredients.

Disadvantages:

(1) Attrition is large, size reduction of friable particles results.

(2) Scale-up can prove a problem, because general principles of scale up do not work.

(3) Cleaning may be a problem, because the agitator assembly must be removed and the packing should be replaced for a product changeover.

(4) Potential packing (sealing) problems.

Ribbon Blender

Principle : The mechanism of mixing is shear. Shear is transferred to the powder bed by moving blades (ribbon shaped) in a fixed (non-movable) shell. High shear rates are effective in breaking lumps and aggregates. Convective mixing also occurs as the powder bed is lifted and allowed to cascade to the bottom of the container. An equilibrium state of mixing can be achieved.

Construction : The construction of a ribbon blender is shown in Figure 9-11. It consists of a non-movable horizontal cylindrical trough usually opens at the top. It is fitted with two helical blades, which are mounted on a drive shaft through the long axis of the trough. The blades have both right and left hand twists. The driver shaft is connected to a fixed speed drive. Ribbon blender is top loading with a bottom discharge spout. The trough can be closed with a lid.

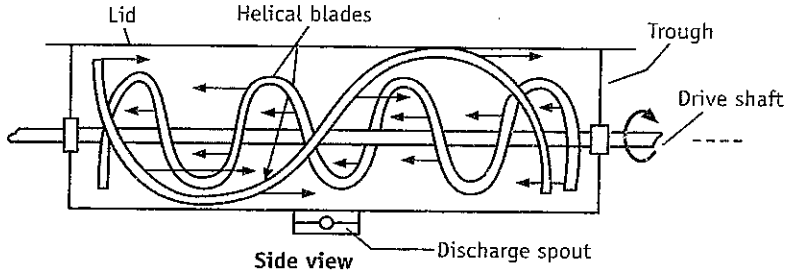


Figure 9-11. Ribbon mixer. Stationary shell and rotating blades.

Working : Through the fixed speed drive, ribbons are allowed to rotate. One blade moves the solids slowly in one direction and the other moves them quickly in opposite direction. Different powders are introduced from the top of the trough. The body is covered because consid-

erable dust may be evolved during dry blending and granulating medium may evaporate during wet granulation.

The agitator blade rotates, lifts and distributes the material in an irregular manner. Convective and shear mixing occur as well as some fine-scale diffusive mixing occurs. The counteracting blades set up high shear and are effective in breaking up lumps or aggregates. Helical blades move the powders from one end to another as shown in Figure 9-11. The final stage of mix represents an equilibrium state. The operating conditions of a given mixer can markedly effect the steady state and thus the quality of the mixing. The blend is discharged through discharge spout or by inverting the ribbon blender.

Uses : Ribbon blender is used to mix finely divided solids, wet solid mass, sticky and plastic solids. Uniform size and density material can be easily mixed. It is used for liquid-solid and solid-solid mixing.

Advantages : High shear can be applied using perforated baffles, which bring about rubbing and breaking of aggregates. Headroom requirement is less. It can also be used as continuous blender by feeding material at one end and discharging at the other end.

Disadvantages : (1) It is a poor mixer, because movement of particles is two-dimensional.

(2) Shearing action is less than in planetary mixer.

(3) Dead spots (areas that remain unmixed) are observed in the mixer, though they are minimum.

(4) It is having fixed speed drive.

Sigma Blade Mixer

Principle : The mechanism of mixing is shearing. The inter-meshing of sigma shaped blades creates high shear and kneading actions. Convective mixing is achieved by cascading the material.

Construction : The construction of a sigma blade blender is shown in Figure 9-12. It consists of double trough shaped stationary bowl. Two sigma (indicating the shape of the *Greek* letter) shaped blades are fitted

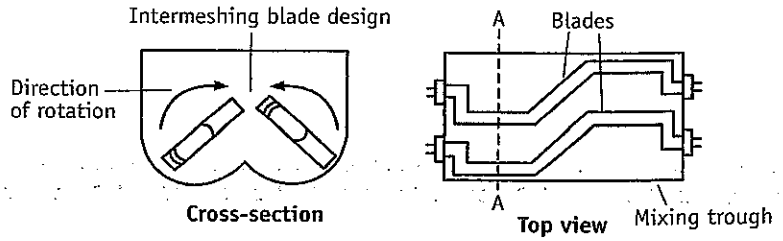


Figure 9-12. Sigma blade mixer. Stationary shell and rotating blades.

horizontally in each trough of the bowl. These are connected to a fixed speed drive. The mixer is loaded from the top and unloaded by tilting the entire bowl by means of a rack-and-pinion drive.

Working : Different powders are introduced from the top of the trough. The body is covered because considerable dust may be evolved during dry blending and granulating solution may evaporate during wet granulation.

Through the fixed speed drive, the sigma blades are allowed to rotate. The blades move at different speeds, one usually about twice the speed of other, resulting in lateral pulling of the material. They turn towards each other so that the powders move from the sides to the centre of the bowl. The material further moves downwards over the point and then sheared between the blades and the wall of the trough. Thus cascading action (convective) as well as shear action can be achieved. The perforated blades help in breaking lumps and aggregates. Thus high shear forces are set up. The final stage of mix represents an equilibrium state. The operating conditions of a given mixer can markedly effect the steady state and thus the quality of the mixing. By means of a rack-and-pinion drive the bowl is tilted to empty the blend.

Uses : Sigma blade mixer is commonly used for mixing of dough ingredients in the baking industry. It is used in wet granulation process in the manufacture of tablets, pill masses and ointments. It is primarily used for liquid-solid mixing, although it can be used for solid-solid mixing.

Advantages:

(1) Sigma blade mixer creates a minimum dead space during mixing.

(2) It has close tolerances between the blades and the side-walls as well as bottom of the mixer shell.

Disadvantage : Sigma blade mixer works at a fixed speed.

Planetary Mixer

Principle : In a planetary mixer, the blade tears the mass apart and shear is applied between a moving blade and a stationary wall. The mixing arm moves in two ways, around its own axis and around the central axis, so that it reaches every spot of the vessel. The plates in the blade are sloped so that the powder makes an upward movement. Therefore, tumbling (convective) motion is also obtained.

Construction : The construction of a planetary mixer is shown in Figure 9-13. It consists of a vertical cylindrical shell, which can be removed either by lowering it beneath the blade or raising the blade above the bowl. The mixing blade is mounted from the top of the bowl. The mixing shaft is driven by a planetary gear train, as indicated in the Fig-

ure 9-13. It rotates around the ring gear, which further rotates round the mixer blade. It is normally built with a variable speed drive.

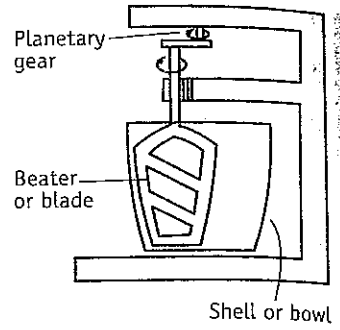


Figure 9-13. Planetary mixer.

Working : In the planetary mixer, the agitator has a planetary motion. It rotates on its own and around the central axis so that it reaches all parts of the vessel. Beater is shaped to pass with close clearance over the side and bottom of the mixing bowl. Therefore, literally there are no dead spaces in the mixing bowl. The blade tears the mass apart and shear is applied between the moving blade and the stationary wall. The plates in the blade are sloped so that the powder makes an upward movement. Therefore, tumbling (convective) motion is also obtained. Since it is a variable speed driven, initially the blade moves slowly for premixing and finally at increased speed for active mixing. Thus high shear can be applied for mixing.

Emptying the bowl may be done by hand (scooping) or by dumping mechanism.

Uses : Planetary mixer produces precise blends in addition to breaking down of agglomerates rapidly. Low speeds are used for dry blending and faster speeds for the kneading action required in wet granulation. Steam jacketed bowls are used in the manufacture of sustained release products and ointments.

Advantages : Speed of the rotation can be varied at will, so it is advantageous over sigma blade or ribbon type blenders. This is more useful for wet granulation process. There are no packing glands in contact with the product.

Disadvantages:

(1) Mechanical heat is built up within the powder mix.
(2) It requires high power.
(3) It has limited size and is useful for batch work only.

Air Mixer or Fluidized Mixer

Principle : The air movement is used for mixing powders. The powders are mixed in a stationary cylindrical vessel. Air is admitted at its base at an angle. This gives tumbling action and spiral movements to the powder. Thus mixing is achieved.

The construction and working of an air mixer or fluidised mixer remains same as shown in fluidised bed dryer in the Chapter 8 Drying.

Advantages : Air mixer shortens the mixing time. It is useful as a through-output. Mixing is intimate and efficient. It is also used for wet granulation in tablets. With additional attachments, this equipment is useful for mixing, wet massing and drying in the wet granulation method. This method is also used for coating with some modifications.

Barrel Type Continuous Mixer

Principle : In a barrel type continuous mixer, the rotating shell keeps the material under tumbling motion. The presence of baffles further enhances the mixing action. When the material approach the mid-point of the shell, another set of baffles causes part of the material to move towards the direction of inlet end, allowing the remaining part to move forward. Such a mechanism provides intense mixing of ingredients. This process continues up to discharge end, where another set of baffles guide the material to the discharge port. The blended material at an equilibrium state overflows from the discharge end.

Construction : The construction of a barrel type mixer is shown in Figure 9-14. It resembles a large cement mixer. Baffles are fitted to the inner surface of the shell. The shell is fixed to a shaft, which is allowed to rotate using electric power. Side openings are provided on each side for charging and discharging of materials.

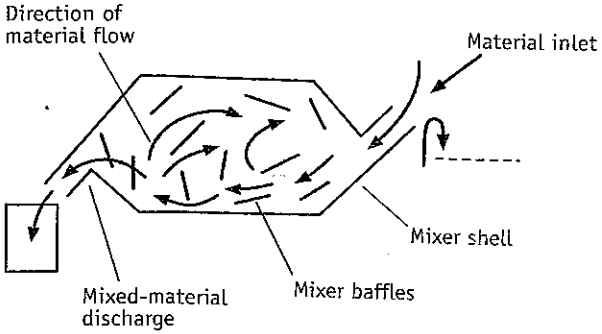


Figure 9-14. Barrel type continuous mixer.

Working : The mixer is allowed to rotate. Along with it the baffles also rotate. The ingredients are introduced into the shell through the inlet. They begin moving towards the opposite end of the blender due to tumbling action. Baffles further enhance the mixing. As the material approaches the mid-point of the mixer shell, the baffles are so positioned to cause the feedback of part of the material in the direction of the inlet end. The movements are shown in Figure 9-14 using arrow markings. The feedback action continues up to the discharge end, where another set of baffles guides the material to the discharge port. The overflow of material causes

the blended solids to discharge. Since charging and discharging are simultaneously done, the process becomes continuous.

Zigzag Continuous Blender

Principle : Zigzag continuous blender is a rotating shell type having several V shaped blenders connected in series. The material undergoes tumbling motion. When the V section is inverted, the material splits into two portions; one-half of material moves backward (into the preceding section), while another-half of material moves forward. Due to inclined axis of the shell towards the discharged end, the material gets discharged. As the first V section clears the charge, a fresh feed enters. Thus, it is used for continuous blending of solids.

Construction : The construction of a zigzag continuous blender is shown in Figure 9-15. The shell takes the shape of several V shaped blenders connected in series. A chamber for charging is attached to one end of the shell. The other end allows the discharge of material. The shell is inclined towards the discharge end.

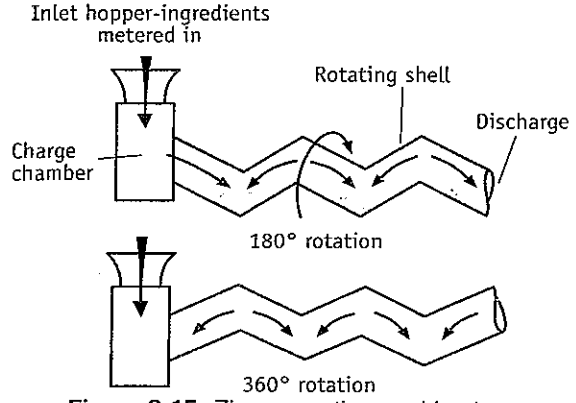


Figure 9-15. Zigzag continuous blender.

Working : A single pre-weighed charge is introduced into the charge chamber. As the shell rotates, at one particular angle a metered material enters the V-shaped section by gravity (Figure 9-15). With each rotation, one-half of the blend material moves downward back to the preceding leg and another-half of the material moves forward to the next leg of the blender. In each rotation, a part of the material moves towards the discharge end.

As the first charge clears the first V section, which may take only a few minutes, the next charge is added. The uniformity of blending depends on the flow properties of the ingredients.

Automatic Processing of Blending

In-line mixing system is useful to blend active substances and excipients without modifying their physical properties, without cross-contamination, ensuring safety to operators and environment. The powder transfer system (PTS) performs the activities of transferring, mixing and discharging products automatically using vacuum and pressure under inert conditions. In a continuous type, delivering the excipients and removing the products are often critical than the choice of mixing equipment. The pneumatic transfer uses air to suspend the particles in the moving air. Depending on the concentration of solids, air-aided transfer may be considered as dense or dilute phase. The in-line system unit should be useful to mix hygroscopic, oxygen sensitive or explosive powders. The unit needs to have the flexibility of blending powders with large differences in blend ratios (1:10,000) and different properties.

Comment 9-5. Dead spots are objectionable in a blender. True or false. Explain.

Comment 9-6. Can one equipment be used for the mixing of different types of materials?

Comment 9-7. Fluidized air is used for conveying, drying and size reduction. Can it be used in mixing of powders? Explain.

SELECTION OF SOLID MIXING EQUIPMENT

An ideal mixer or blender must achieve the specified quality of the final product in a very short time using a stable and repeatable process, with minimum residual product in the machine and cleanability. Selecting a right kind of equipment is attempted after thorough analysis. The factors considered while selecting the mixing equipment are given below.

Material Characteristics

Process Setup Requirements

- Blending accuracy, blending time
- Flexibility of batch volume
- Product contamination risk
- Requirement for complete product discharge
- Operating efficiency
- Cleaning between batches

Capital Costs, Operating Costs, Plant Layout Considerations

The specialty products and individual drugs are produced in smaller quantities. In such cases, scale down production is important.

Material Characteristics

Dry powder blending is achieved by ribbon and tumbling blenders, adhesive mixtures are blended with multi-shaft blenders, wet granulation requires planetary mixer. The density, viscosity and miscibility determine the selection of equipment. Some of the characteristics are given in Table 9-6.

TABLE 9-6
Material Properties and Selection of Blenders

Material type	*Blender selection*
Non-cohesive blend (free flowing, powders, granules, some slurries).	Twin shell blender, bin blender ribbon blender.
Cohesive blend (non free flowing, lumpy, Granules, some slurries).	Twin shell blender (high shear), paddle mixer.
Ordered mix (drug << excipient).	Tumbling mixer, cone mixer.

Process Setup Requirements

Batch size must be optimal : The mixer design of big size may not give homogeneous mixing. If the volume is large, then the mixing time may be extended. The intended process whether a batch type or continuous type is decided. The extent of segregation after mixing and size reduction (during mixing) is considered.

Blending accuracy, blending time : Rotation speed is an optimal value. If the speed is too low, there would be no agitation, but at low speeds, avalanching flow can occur. At high speed, centrifugal force throws all the material to the perimeter. Some powders required gentle mixing, the design parameters influencing are cross contamination and operating pressures. Excessive mixing can promote segregation. Size is considered keeping in mind the optimal working volume, fill level and residence time. The optimal working volume is nearly 50 to 70 % of the maximum. The Froude number is a relevant scaling parameter.

Flexibility of batch volume : A blending system is expected to mix a wide number of powders. Similarly, handling of different batch sizes and also different blend ratios is essential. The equipment should readily integrate with upstream/downstream equipment, because labour costs are continuously increasing. Further, batch size, viscosity, vacuum capability, temperature, contact and scalability are a few considerations.

Product contamination risk : The chances of cross-contamination need to be considered. If the product is potent, then cleaning considerations should be given.

Requirement for complete product discharge : In case of discharge, the blender empties fully and smoothly with no residual content. Smooth internal finish is necessary.

Power consumption : *Power consumption or energy efficiency* is a vital factor. The choice of agitator determines the efficiency.

Cleaning between batches : In some situations, frequent cleaning may be essential, particularly when potent products are handled. The facilities such as CIP (clean-in-place) is need to be provided.

Capital Costs, Operating Costs

The number of components needed to perform a particular task influence the costs, initial costs and rising costs for cleaning, maintenance, product loss and safety.

Plant Layout Considerations

Not only the space required for installation of mixer, but also the accessories that are meant for loading, discharging and connecting to the downstream operations should be considered. The mixing vessel may be fixed at one place (double cone blender) or transported to a different place for loading and discharging.

Summary

Mixing of solids means randomization of dissimilar particles within a system. Mixing is an unit operation and solid mixing is not an easy task, because solid particles are available in diverse nature, size, shape, volume, surface area, density, porosity, flow, charge, etc. Mixing of cohesive particles is still a difficult task. Solid mixing is not simple compared to liquid mixing. Mixing can also be wet mixing or dry mixing. Mixing is an important unit operation in the formulation of tablets, capsules, dry powders, insufflations, etc. Segregation is opposite to mixing. The mixing of particles is an interplay of inertial and gravitational forces. The principal mechanisms of solid-solid mixing are: convective mixing, shear mixing, and diffusive mixing. The mixing of solids involves a number of steps and expected to attain random mixing. Once the mixing is stopped, the blend should exist in static equilibrium. The degree of mixing is also known as degree of homogeneity. Mixing process is indicated by several terms such as ideal mixing (or perfect mixing), acceptable mixing (random mixing and order mixing), etc. Acceptable mixing is considered as adequate, but it should be expressed clearly using statistical parameters, such as arithmetic mean, standard deviation, relative standard deviation (RSD), mixing index, etc. The selection of mixing equipment depends on several factors including appropriate sampling methods.

The mixing equipment should produce the desired characteristics and at the same time, should not cause segregation of particles. Some of the equipment are tumblers with no mixing blade. These are used at a laboratory level. Twin-shell blender is made up stainless steel and can take charge of 20 kg of the feed and operates at a speed of 35 rotations per minute (rpm). Similarly double cone blender is also used with 80 to 100 rpm. It is routinely used for mixing in tablet/capsule production. Ribbon blender works on the mechanism of shear and is suitable to wet mixing as well as dry mixing. The blender is fitted with helical blades and has right-hand and left-hand twists. The powder is lifted up and allowed to cascade to the bottom in the cylindrical trough. Mixing is continued until

equilibrium condition is achieved (as measured by mixing index). It is also useful for liquid-solid mixing. Sigma blade mixer is used in granulation process in which mixing as well as granulation can be achieved. In this type, two horizontally fitted sigma shaped blades allow the mixing. It has minimum dead spots. Planetary mixer is a vertical cylindrical shell in which the blade works from a planetary gear, i.e. it moves around its own axis and also around the central axis. The plates of the blade are sloped so that powder makes upward movement and tumbling motion is achieved. It has a distinct advantage of variable speed and no dead spots. In air mixer, tumbling action is achieved, because air admitted from the base at an angle lifts the solids up and allowed to fall. This allows solid-mixing, wet mass mixing and also coating of granules. Barrel type mixer is used for a continuous process. Inside walls of the barrel is fitted with baffles. Shell is fitted with a shaft which is allowed to rotate. The side openings on both sides served as inlet and outlet, respectively, for feed entry and product discharge. Zigzag blender is also used for continuous mixing. The material undergoes tumbling, while material moving from the feed enters into 'V sections' and 'inverted V sections' continuously. The flow properties of the materials decide the overall mixing uniformity.

Glossary of Symbols (Section-I)

A = Constant.
a = Overall fraction of tracer in the mixture.
t = Time, min.
k = Constant.
M = Degree of mixing or mixing index at time, t.
n = Number of samples.
RSD = Relative standard deviation.
σ = Standard deviation.
σ_0 = Standard deviation of unmixed powder.
σ_R = Standard deviation of random blend.
$\bar{y}$ = Arithmetic mean (particle size or concentration).
y = True mean of the standard.
y_i = The value of a given sample.

QUESTION BANK

Each question carries one mark

Note : Encircle the alphabet which corresponds to the single best response.

1. Which of the following produces randomisation during mixing unit operation?
   A. Dissimilar charges
   B. Dissimilar forces
   C. Dissimilar ions
   D. Dissimilar particles

2. Which of the following arrangements involved in a static mixer?
   A. Shell and blade are stationary
   B. Shell and blade rotate
   C. Shell is stationary and blade rotates
   D. Shell rotates and blade is stationary
3. In which type of mixer, the trough is stationary?
   A. Barrel mixer
   B. Double cone blender
   C. Ribbon mixer
   D. Zigzag mixer
4. Which of the following forces aids the tumbling action for promoting inter-particle movement?
   A. Electrostatic force
   B. Gravitational force
   C. Surface force
   D. Van der Walls force
5. Which one of the following rates (kinetic orders) is observed in the mixing of solids?
   A. First order
   B. Pseudo-first order
   C. Second order
   D. Zero order
6. Which type of particle-particle interactions is experienced on account of surface charges produced during mixing of solids?
   A. Attractions
   B. Collisions
   C. Diffusion
   D. Repulsions
7. Which one of the following is NOT an example for inertial forces?
   A. Electrostatic forces
   B. London forces
   C. Surface forces
   D. Van der Waals forces
8. In dispensing, which one of the following terms is NOT used for mixing?
   A. Sizing
   B. Spatulation
   C. Trituration
   D. Tumbling
9. Solid mixing does NOT differ from liquid mixing in one of the following ways.
   A. flow currents are not possible
   B. homogeneity of components
   C. large sample is required for analysis
   D. mixing requires high power
10. Mixing of ingredients is a problem when
    A. amount of active constituent is low
    B. dose of drug is high
    C. materials are non-cohesive
    D. shape of components are similar
11. Uneven mixing leads to one of the following problems in tablets manufacture?
    A. Content uniformity variation
    B. Disintegration time fluctuates
    C. Friability problems
    D. Poor flow of granules

12. Practically one of the following mixing patterns is closer to the real situation?
    A. Ideal mixing
    B. Ordered mixing
    C. Perfect mixing
    D. Random mixing
13. Which mixing equipment produces tumbling as the only mechanism in solid-solid mixing?
    A. Fluidised mixer
    B. Ribbon blender
    C. Sigma blender
    D. V-cone blender
14. Name the mechanism in which adjacent particles (in a powder bed) are transferred to another location.
    A. Convective mixing
    B. Diffusive mixing
    C. Negative mixing
    D. Positive mixing
15. Convective mixing is also termed as:
    A. diffusive mixing
    B. macro-mixing
    C. micro-mixing
    D. shear mixing
16. The statistical parameter 'standard deviation' is one of the indicators for mixing of powders.
    A. Mixing indices
    B. Scattering of particles
    C. Segregation of particles
    D. Uniformity of mixing
17. Which type of action is required for wet granulation, when planetary mixer is used?
    A. Agitatory action
    B. Blending action
    C. Kneading action
    D. Shearing action
18. What is the shape of mixing element present in Zig-zag mixer?
    A. Cube shape
    B. Double cone shape
    C. Sigma shape
    D. V-shape
19. Degree of mixing is also known as:
    A. index of homogeneity
    B. extent of mixing
    C. ordered mixing
    D. random mixing
20. The major mechanism of mixing in sigma blade is:
    A. convective mixing
    B. diffusive mixing
    C. shearing
    D. tumbling
21. The segregation, the process of moving smaller particles into voids between larger particles and reaching the bottom of powder, is known as:
    A. Elutriation
    B. Fluidization
    C. Percolation
    D. Trajectory
22. When compared to spherical particles, non-spherical particles behave in one of the following ways.
    A. Decreases the ratio of surface area to weight
    B. Exhibits increased flowability
    C. Segregates easily
    D. Shows cohesive effects

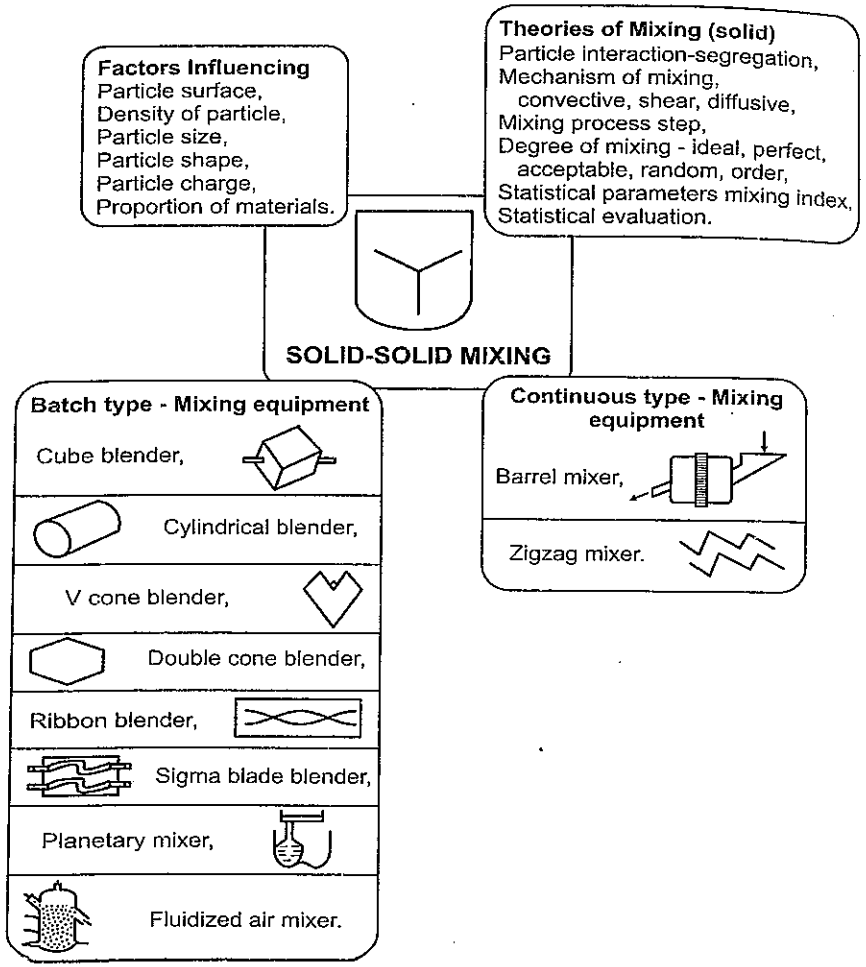
23. The index of mixing of powder is NOT associated with one of the following processes.
    A. Decreasing segregation
    B. Depends on amount of carrier particles
    C. Increasing the flow
    D. Mixing for more time

Each question carries 2 marks

1. List four applications of solid mixing.
2. Differentiate the mixing processes of solids and liquids
3. List two examples each for cohesive powders and non-cohesive powders with their nature.
4. List four properties of cohesive powders considered for powder mixing.
5. List the mechanisms of solid mixing with two examples of mixing equipment for each.
6. What are the differences between random mixing and acceptable mixing?
7. List the evaluation methods of solid mixing along with statistical parameters for their analysis.
8. Suggest two solid mixing equipment each for batch type and continuous type.
9. Differentiate blades and baffles in solid mixing equipment.
10. Explain the differences in mixing mechanisms with solid mixing equipment with a blade and without a blade.
11. What is meant by dead spots in the solid mixing equipment? How can they be prevented?
12. What are the advantages of variable speed blade in a solid mixing equipment?
13. Air mixer is not suitable for solid mixing. True or false. Justify.
14. Two-blade equipment is better than one-blade equipment for solid mixing. Explain.
15. Jacketed bowel is necessary for solid blending. True or false. Justify.
16. Why are dead spots not formed in a planetary mixer?
17. It is not necessary to purchase complicated and expensive equipment for liquid mixing. Explain.

Each question carries 5 marks

1. Explain the reasons for powder segregation in solid mixing and suggest remedial measures.
2. Describe the steps involved in solid mixing along with its kinetics.
3. Explain the phenomenon of ordered mixing with models.
4. Explain the criteria for handling the equipment for solid mixing.
5. Describe the situation which warrant mixing and suggest the equipment with reasons.



MINDMAP OF SOLID-SOLID MIXING UNIT OPERATION

Section II—MIXING OF LIQUIDS

Mechanisms of Liquid Mixing
Mixing Vessels or Tanks
Liquid Mixing Devices — Flow Pattern
Liquid Mixing Equipment

LEARNING OBJECTIVES

After reading this chapter, the reader should be able to:

- Appreciate the applications of liquid mixing.
- Understand the mechanisms involved in the liquid mixing.
- Explain the designs of mixing vats, mixing devices and flow patterns.
- Describe the designs of industrial scale liquid mixing equipment along with working and uses.

Agitation refers to the induced motion of a material in a specified way, usually in a circulatory pattern inside a container.

Mixing refers to the random distribution into or through one another of two or more separate phases.

Liquid-liquid mixing is considered as a simple operation compared to that of solid-liquid mixing. It involves the formation of a homogeneous system. Similar to solid-solid mixing, fluid (or liquid) mixing also involves the application of shear. Agitation and mixing are not synonymous.

Mixing of miscible liquids and solid-liquid can be achieved by a low level of shear mixer. The blending application is related mostly to pumping, i.e. sending the components around the mixing vessel. An axial movement of fluid is sufficient. The nature of liquids mainly determines the ease of mixing. According to theories of solutions, liquid mixtures are classified as follows.

(1) **Miscible liquids :** These are miscible in all proportions. For example, ethyl alcohol and water are miscible in all proportions. These liquids can be mixed easily by employing the mechanisms of bulk transport and shear. Cosmetics (after-shave lotions) and elixirs, belong to this class.

(2) **Partially miscible liquids :** These are miscible in one another at one particular proportion. Their miscibility depends on temperature and pressure. For example, *p*-cresol and water are miscible in a certain proportion. Mixing poses certain difficulties in the preparation of disinfectant solutions.

(3) **Immiscible liquids :** As the name indicates, these are not miscible. For example, vegetable oils and water are not miscible or their miscibility is very low. Normally, they form emulsions. Mixing of these liquids is very difficult. A homogeneous dispersion may be obtained by adding emulsifying agents. Mixing them requires high shear.

The mixing of immiscible liquids is discussed as a separate section. In pharmacy, one of the liquids most commonly used is water. A number of solid and liquid ingredients are added in the formulation of dosage forms. Based on the shear stress-shear rate relationship, fluids are classified as Newtonian and non-Newtonian systems. The general flow characteristics of the fluids have been discussed in the *Textbook of Physical Pharmaceutics-II*, by C.V.S. Subrahmanyam (Vallabh Prakashan, Delhi).

Applications of Liquid Mixing

Liquid mixing promotes heat transfer between liquid and a heating source. This step is essential in the crystallization of drug substances. Uniform heat transfer in the solution yields crystals of same size. For example agitated batch crystallizer works on this principle.

Liquid mixing process is essential in the manufacture of a number of dosage forms. Some of them are listed below.

Preparations	*Phases mixing*	*Examples*
Suspensions	Solid-liquid	Calamine lotion
Emulsions	Liquid-liquid (immiscible)	Benzyl benzoate emulsion
Solutions	Soluble solid-liquid	B Complex elixir
Solutions	Soluble liquid-liquid	Alcohol-water (elixir) Chloroform-water (preservative)
Aerosols	Liquid-gas	Salbutamol inhaler

Comment 9-8. The nature of miscibility of liquids should be known for selecting the mixing equipment. True or false. Justify.

MECHANISMS OF LIQUID MIXING

The mechanisms of liquid mixing can be studied under four classes. They are:

- Bulk transport
- Turbulent mixing
- Laminar mixing
- Molecular diffusion

Bulk Transport

Bulk transport is defined as the movement of a large portion of a material from one location to another location in a given system.

For this purpose, mixing devices such as rotating blades and paddles are used, which moves the material in different directions.

Turbulent Mixing

Turbulent mixing is defined as mixing due to turbulent flow, which results in random fluctuation of the fluid velocity at any given point within the system.

In the turbulent flow, fluid velocity at a given point fluctuates continuously in three directions, x, y and z. However, the liquid moves in one direction depending on the dominant component. In general, the liquid has different velocities at different locations at the same time.

Turbulent flow is a highly effective mechanism for mixing. Turbulent flow can be seen as a composite of eddies of various sizes. An *eddy* is defined as a portion of fluid moving as a unit in a direction. Large eddies tend to break up forming eddies of smaller size, until they are no longer distinguishable. An additional characteristic of turbulent flow is its intensity, which is related to the velocities with which eddies move.

Laminar Mixing

Laminar mixing is the mixing of two dissimilar liquids through laminar flow, i.e. the applied shear stretches the interface between them.

In this mechanism, layers fold back upon themselves. Thus the number of layers increases. Hence, the interfacial area between them also increases exponentially with time. Mixing may also result in simple stretching of the fluid layers without any significant folding action. This is also suitable for liquids, which require moderate mixing.

Molecular Diffusion

Molecular diffusion is the mixing at molecular level in which molecules diffuse due to thermal motion.

Molecular diffusion is explained by the Fick's law, which depends on the concentration gradient at different regions. The concentration gradient decreases with time and it reaches zero when mixing is completed, i.e. equilibrium condition. When molecular diffusion and laminar flow occur simultaneously, molecular diffusion reduces the sharp discontinuities at the interface between the two layers.

Simultaneously more than one mechanism may operate during mixing.

MIXING VESSELS OR TANKS

The mixing apparatus consists of a container (tank) and a mixing device. These are assembled and used for a batch process. The general construction of the mixing tank or container is shown in Figure 9-16 along with other accessories required for mixing. A mixing device is called impeller, which is mounted with the help of a shaft. The shaft is driven by a motor.

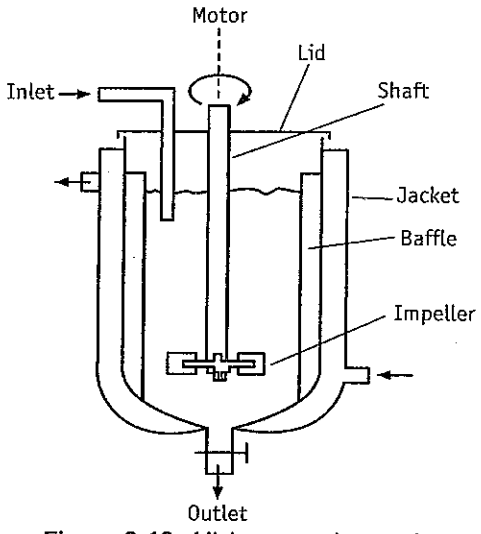


Figure 9-16. Mixing vessel or tank.

The tank is made up of stainless steel. The top of the tank may be open or closed. It is constructed with tank diameter to liquid height ratio of 1:1. The size of the tank depends on the nature of the agitation method. The tank bottom is rounded (not flat) to eliminate sharp corners or regions into which fluid would penetrate. It also carries an outlet, coils, jackets, temperature measuring device etc. wherever necessary. Turbines agitator operate in the 20-120 rpm range, which is low shearing and low initial costs.

Baffles : Containers can be either baffled or unbaffled. Baffled containers are those in which metal strips (baffles) are placed vertically to the internal surface. When bulk transport is important in mixing, baffles are used. These are particularly desirable in the initial stages of mixing when segregation is present on a large scale. Baffles facilitate intermingling of the liquids even from remote regions of the mixer.

In most of the cases four baffles are sufficient. Even one or two baffles provide a strong effect on mixing. The width of the baffle may be from 1/10th to 1/18th of the tank diameter. If solids are present in the liquid to be mixed, the baffles are fixed with a gap of about 25 mm between the baffle and the tank surface.

The above discussion includes containers in which the liquids move. In some cases, the container itself moves to mix the liquids, e.g. *shaker mixer*. Oscillatory movement is applicable on a small scale whereas rotary movement is applicable on a large scale. Shaker mixers are rarely used in pharmacy.

LIQUID MIXING DEVICES — FLOW PATTERN

Mixing devices are used to supply energy to the system so long as to bring about reasonably rapid mixing. It is necessary to justify the economy of the equipment through trails.

- A multipurpose mixing device can give the necessary shear rate depending on the material.
- A low shear mixer used for solids can as well be used for liquid mixing.

Normally, liquid mixing is batch process, particularly in the production of liquid dosage form. It is also possible to change the formulation ingredients, so as to use the existing mixer, rather than purchasing new liquid mixing equipment. Convenience and cost of equipment is considered. Flow currents are responsible for transporting unmixed materials to the mixing zone.

Pitch is defined as the distance the impeller would move through the fluid per revolution, if slippage does not occur.

Mixing devices are technically called as *impellers*. Impellers are classified on the basis of the shape and pitch of the blades that are attached to the central shaft. Three main types of impellers are used namely, propellers, turbines and paddles. These are discussed below.

Propellers

A propeller normally contains a number of blades (Figure 9-17). A three bladed design is the most common for liquids. The marine type propeller is similar to the blades of a table fan or a ceiling fan.



Figure 9-17. Propeller type of mixing devices. A three bladed design.

Propellers may be either right or left handed, depending on the direction of slant of their blades. Four bladed or toothed or similar design propellers are used for special purposes. In a deep tank, push-pull propeller is used in which two or more propellers may be attached to the same shaft. These work in opposite directions to create a zone of high turbulence. The size of the propeller is small, i.e. the ratio of diameters between propeller and container of 20 is sufficient for low viscous liquids. However, for large tanks the maximum size of 0.5 m propeller is used. Small propellers turn at full motor speed up to 8000 rotations per minute.

Propellers are available come in different diameters ranging from a few inches to 3 ft depending on the manufacturers. The impellers made of cast construction are available at low costs. Propellers with 300-400 rpm are used for low speeds and at high speeds, the rotation is 1750 rpm. This parameter depends on the viscosity of the material. Since impellers produce shear and pump differently, it is important to make sure that the size, speed and power are checked before purchasing. The other information are: viscosity, density, vessel configuration and the desired process are also considered.

The propeller produces axial (longitudinal) movement of the liquid. The flow currents leaving the propeller continue through the liquid in a given direction until deflected by the floor or wall of the tank. For large batch size over 500 gallons, marine propeller mixer is not an optimal choice. Turbines are a better choice.

Uses : Propellers are used when high mixing capacity is needed. These are effective in handling liquids having a maximum viscosity of about 2.0 pascals·second and slurries up to 10 % solids of fine mesh size. They can be used upto 3.5 m^3 (or 3500 L). Effective gas-liquid dispersion is possible at the laboratory scale. Multivitamin elixir, disinfectant solutions are manufactured using propellers.

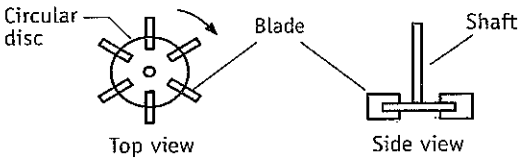
Disadvantage : Propellers are not normally effective with liquids of viscosity greater than 5 pascal·second, e.g. glycerin and castor oil.

Turbines

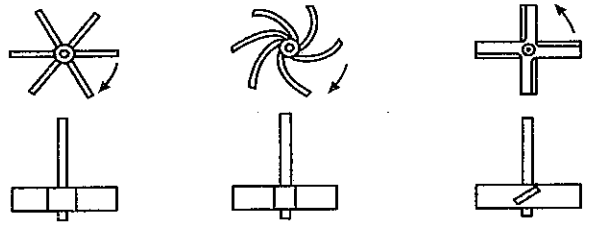
A turbine consists of a circular disc to which a number of short blades are attached. (Figure 9-18a). The diameter of the turbine ranges from 30-50 % of the diameter of the vessel. It rotates at a lower speed than propeller (50-200 rotations per minute). Different forms of turbines are shown in Figure 9-18. The blades may be straight, curved, pitched or vertical. For these reasons, turbine mixers are considered as versatile. The parameters of the turbines are:

- Impeller diameter,
- Rotation speed,
- Blade angle,
- Number of blades,
- Blade shape.

These are extensively studied. When impellers are not the best choice, turbines are chosen. These can handle large volume up to 1000 gallons. A flat bladed turbine produces radial and tangential flow, but as speed increases, radial flow dominates. A pitched blade turbine produces axial flow.



(a) General assembly of blade disk turbine or flat bladed turbine.



(b) Various types of blades.

Figure 9-18. Turbine impeller (or mixing element).

Near the impeller, the zone of rapid currents, high turbulence and intense shear is observed. The shear produced by turbines can be further enhanced using a diffuser ring. A diffuser ring is a stationary perforated or slotted ring, which surrounds the turbine. It increases shear forces. The liquid passes through the perforations reducing rotational swirling and vortexing.

Uses : Turbines are effective for high viscous solutions with a very wide range of viscosities upto 7,00 pascal·seconds. E.g. syrups, liquid paraffin and glycerin. In low viscosity materials of large volumes, turbines generate strong currents (intense shear) which spread throughout the tank destroying stagnant pockets. They can handle slurries with 60 % solids. Turbines are suitable for liquids of large volume and high viscosity, if the tank is baffled.

Advantages : Turbines give greater shearing forces than propellers, though the pumping rate is less. Therefore, turbines are suitable for emulsification.

Paddles

A paddle consists of a hub centrally with two long flat blades attached to it vertically (Figure 9-19).

Paddles with two blades or four blades are common. Sometimes, the blades are pitched to increase the axial flow. In some paddles, the blades are dished or hemispherical in shape and have a large surface area in relation to the tank in which they are used. Because of this shape, paddles pass

close to the tank walls and effectively mix viscous liquids, avoiding dead spots and deposited solids.

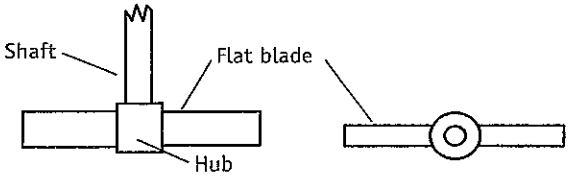


Figure 9-19. Paddle type of agitator or impeller.

- Paddle with upper-blade and lower-blade is suitable for mixing of miscible liquids with low viscosities. A tangential flow pattern predominates.
- As the operating speed increases, the ratio of radial to tangential flow increases.
- Gate paddle is similar for mixing of liquids of high viscosities.
- Stationary blade inter-meshing with the moving element suppress swirling in mixing.
- Anchor paddle with low clearance between pan and blade is useful for working across the heat transfer surfaces.

A shaft carrying hub-blades rotates at a low speed of the order of 100 rotations per minute. They push the liquid radially and tangentially with almost no axial motion unless the blades are pitched. In deep tanks several paddles are attached one above the other on the same shaft. At very low speeds it gives mild agitation in an unbaffled tank, where as for higher speeds baffles are necessary. Otherwise, the liquid is swirled around the vessel with little mixing.

Uses : Paddles are used in the manufacture of antacid suspensions (aluminium hydroxide gel and magnesium hydroxide), agar and pectin related purgatives, antidiarrheal mixtures such as bismuth-kaolin.

Advantage : Vortex formation is not possible with paddle impellers because of low speed mixing.

Disadvantage : Mixing of the suspension is poor, therefore, baffled tanks are required.

Flow Pattern During Mixing

Liquids are mixed usually by impellers, which produce shear forces for inducing necessary flow pattern in the container. Mixing takes place due to the resultant effect of three components acting on the liquid. These are radial component, longitudinal component and tangential component (Figure 9-20).

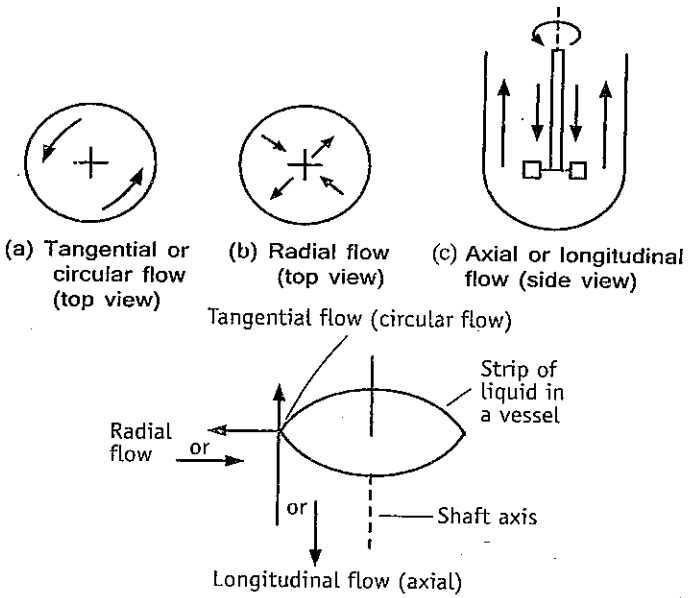


Figure 9-20. Diagrammatic representation of a cylindrical tank with tangential, radial and axial flow. Each diagram represents one type of flow (a, b, and c). In usual situations, one or more or a combination of these flow patterns occur simultaneously (d).

Tangential component (or circular) : It acts in a direction tangent to the circle of rotation around the impeller shaft (Figure 9-20a). If shaft is placed vertically and centrally, tangential flow follows a circular path around the shaft and creates a vortex in the liquid.

Radial component : It acts in a direction vertical to the impeller shaft (Figure 9-20b). Excessive radial flow takes the material to the container wall, then material falls to the bottom and rotate as a mass beneath the impeller.

Axial component (or longitudinal or vertical) : It acts in a direction parallel to the impeller shaft (Figure 9-20c). Inadequate longitudinal component causes the liquid and solid to rotate in layers without mixing. Adequate longitudinal pattern is best used to generate strong vertical currents particularly when suspending solids are present in a liquid.

A satisfactory flow pattern depends on the correct balancing of these components. The radial flow gives rise to axial flow by reaction at the wall of the tank. The tangential flow do not change or modify into any other form of movement. Normally, tangential flow is minimized by placing the impeller to an off centre position. This configuration destroys the symme-

try of the mixer or modifies the flow pattern by means of baffles attached to the walls of the tank. These reduce, but do not eliminate the tangential flow. Baffles do not modify the radial and axial flow.

TABLE 9-7
Flow Patterns of Impellers

Impeller type	*Flow component*
Propellers	axial
Turbines	axial or tangential or both
Paddles	radial and tangential not axial
Paddles with pitch	radial, tangential and axial

These may occur either in single or in various combinations. A satisfactory flow pattern depends on the balance of the components. The flow patterns of different impellers are given in Table 9-7. Axial flow designs produce high pumping flow rates (i.e. turbulence) than the radial flow.

Vortex Formation

A strong circulatory flow pattern sometimes manifests into formation of a vortex near the impeller shaft (Figure 9-21).

Vortex can be formed when:

- The shaft is mounted vertically in the centre of the tank, i.e. symmetry. Such a mounting tend to induce tangential flow.
- Blades in the turbines are arranged perpendicular to the central shaft.
- At high impeller speeds.
- In unbaffled tanks.

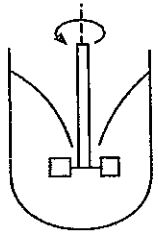


Figure 9-21. Vortex formation with a turbine type impeller (Similar pattern is observed with propeller type also).

Disadvantages : Vortex formation reduces the mixing intensity by reducing the velocity of the impeller relative to the surrounding fluid. When vortex reaches the impeller, air from surface of the liquid is drawn. This is an undesirable situation, because air bubbles are difficult to remove. The entrapped air causes oxidation of the substances in certain cases. The air bubbles in the fluid can create uneven loading of the impeller blades.

Prevention of vortex formation : Vortex formation can be prevented by any one of the following methods (Figure 9-22).

(1) Impeller should be mounted in any one of the positions to avoid symmetry (Figure 9-22.1). At the same time, it should be deep in the liquid.

When the propeller is placed off centrally, a small amount of tangential flow is induced. This discharge stream will offset the swirl induced by its rotation (Figure 9-22.1a).

A similar effect can be observed by placing the propellar in an inclined position (Figure 9-22.1b).



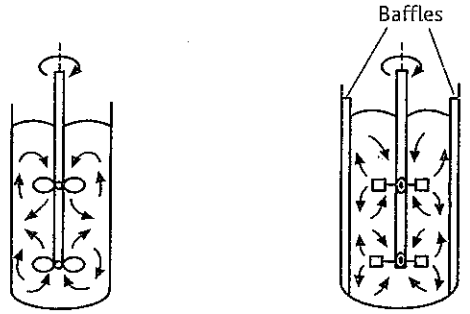
(a) Off center (b) Inclined (c) Side entry

1. Positions of propellers with flow pattern in a vessel to prevent vortex.



(i) Centrally placed propeller in a baffled tank, side view (ii) Centrally placed propeller in a baffled tank, top view

2. Arrangement of baffles and flow pattern in a vessel to prevent vortex.



(a) Propeller in an unbaffled tank (b) Turbine in a baffled tank

3. Arrangement of push-pull mechanism with flow patterns in a tank to prevent vortex

Figure 9-22. Positions of impellers with flow pattern in a vessel to prevent vortex formation and gas entrapment.

In side entering propeller, swirl is seldom a problem. This geometry provides a baffling effect and results in circulation of material from the top to bottom in a vessel (Figure 9-22.1c). The disadvantage for this position is

leakage, therefore, the packing round the shaft must be secured. Side entry is also a source of contamination, which is difficult to clean.

(2) Baffled containers should be used (Figure 9-22.2i). In such a case, impeller can be mounted vertically at the center.

(3) Two or more impellers (propeller or turbine, but not paddle) are mounted on same shaft in a tank where greater depth is desired. This system is known as push-pull mechanism. With such an arrangement each impeller acts as a separate mixer. Two types of flow are produced from impellers. The bottom impeller is placed about one impeller diameter above the bottom of the tank (Figure 9-22.3a and b). It creates a zone of high turbulence.

(4) Tanks other than cylindrical shape are used to prevent vortex formation. However, such shapes may lead to the the formation of dead spots.

Return Flow with Draft Tubes

Draft tubes are placed to control the direction and velocity of the flow to the impeller.

The return flow to an impeller of any type approaches from all directions, because it is not under the control of solid surface. Draft tubes can control it. These are mounted around the propeller (Figure 9-23a). In case of turbines, draft tubes are mounted immediately above the impeller (Figure 9-23b).

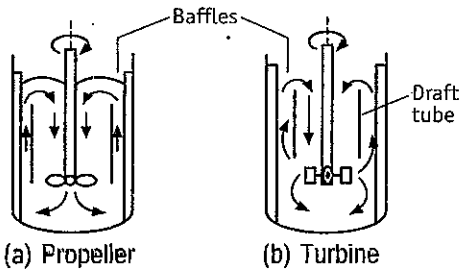


Figure 9-23. Flow pattern of liquid in a baffled tank with draft tubes.

Uses : Draft tubes are fitted to equipment used in the manufacture of certain emulsions. When solid particles tend to float on the surface of the liquid, they are dispersed using draft tubes. Airjet mixers for continuous mixing of liquids employ draft tubes.

Disadvantage : Draft tubes add to the fluid friction in the system. These reduce the rate of flow. So these are used only when required.

Comment 9-9. Explain the differences among the movements, radial, axial and tangential.

LIQUID MIXING EQUIPMENT

The following factors influence the mixing of liquids in tanks. These also help in selecting the equipment.

(A) Material Related Factors

Properties of liquids : Physical properties of the materials to be mixed. Examples are density, viscosity (Newtonian and non-Newtonian) and miscibility (intermolecular attractions).

(B) Equipment Related Factors

Shape of the impeller : Straight, vertical, curved or pitched.

Position of the impeller : Central, off-center, side entry, vertical inclined, etc.

Shape and size of the container : Cylindrical or other geometric forms. Presence or absence of baffles.

Cost of equipment and its maintenance

(C) Process Related Factors

Speed of rotation of the impeller
Time required for mixing
Amount of power that can be expended
Ease of operation
Batch size

The general mixing apparatus are discussed earlier. These are used for batch operations, which involve assembling of different parts. It is also possible to develop continuous mixing equipment. Some of them are discussed below.

Critical Quality Attributes – Liquid Mixing

The CQAs along with process parameters (PPs) are recorded in Figure 9-24. The liquid mixing is considered in the context of production of liquid solutions. The upstream operation must be the dispensing (weighing of raw materials) and the downstream operation is bottling (filling). Thus in the preparation of liquids, mixing is the only step and it is critical. The CQAs became critical and should be attained in this step only. The critical attributes are: assay, viscosity and microbial load.

The process parameters are several and optimization is a laborious process. Thus liquid mixing is a complex process and always attempted for a batch process. The parameters are: impeller speed and time of mixing. These are controlled during mixing using standards with limits. The above are normally universal parameters, though changes are adopted depending on the type of mixing system used.

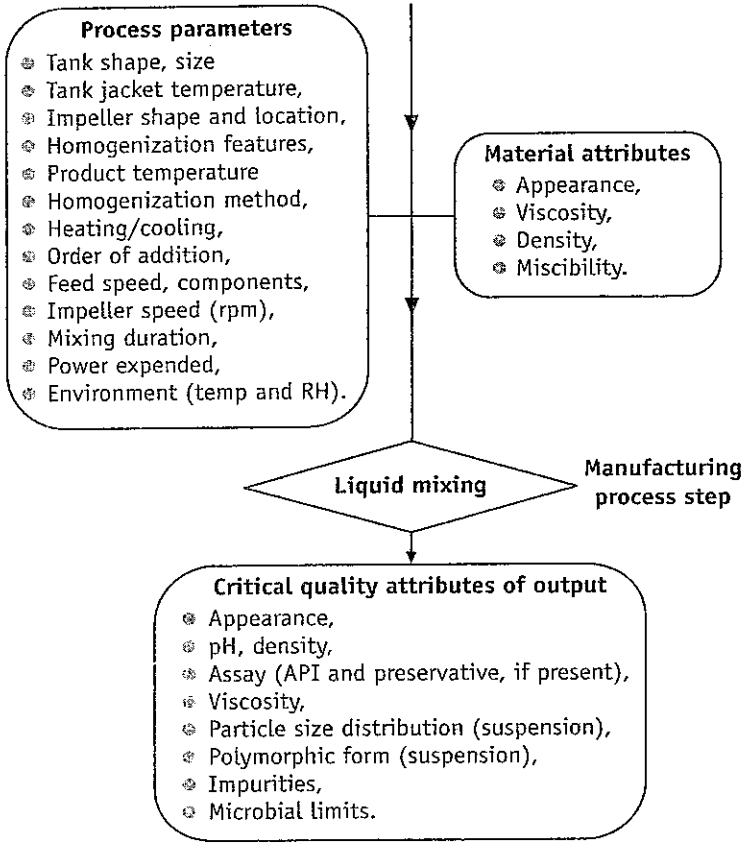


Figure 9-24. CQAs and process parameters for liquid mixing in the production of liquid oral preparations.

Airjet Mixer

Principle : When compressed air jets are passed from the bottom of a vessel, air bubbles are formed in the liquid phase. The buoyancy of the bubbles lifts the liquids, which are confined to the central portion due to the presence of draft tubes. The liquids flow down from the periphery of the vessel and enter the bottom due to suction effect. Thus mixing is achieved.

Working : The assembly of an airjet mixer is shown in Figure 9-25. The liquid is placed in the vessel. Draft tubes are placed surrounding air jet as shown in Figure 9-25. Compressed air or a suitable gas is allowed to pass at high pressure from the inlet provided at the bottom of the tank. This causes buoyancy of the bubbles, which lifts the liquids from bottom to the top of the vessel.

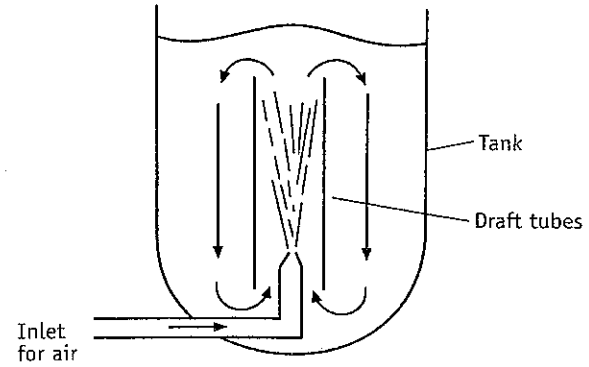


Figure 9-25. Vertical tank with centrally located airjet and draft tube. Mechanism of mixing.

Draft tubes serve to confine the expanding bubbles and entrained liquids to the central portion. This results in a more efficient lifting action by the bubbles. The liquid mixture flows down from the periphery of the vessel. The overall circulation brings liquids from all parts of the vessel to the region of the jet itself. Thus mixing is achieved.

Uses : Liquids of low viscosity, non-foaming, non-reactive with gas are mixed by using airjet mixer.

Jet Mixer

Principle : The liquids to be mixed are pumped separately into a jet mixer at different velocities. The high velocity fluid has a lower static pressure than surrounding liquid (higher static pressure). During mixing, the slow moving liquid will be drawn into the high velocity jet. This increases the volume of the jet and decreases velocity, which causes the jet to expand. Thus shear is developed and aids in mixing.

Working : The construction of a jet mixer is shown in Figure 9-26. Two liquids are introduced into the mixing tank at different velocities. One

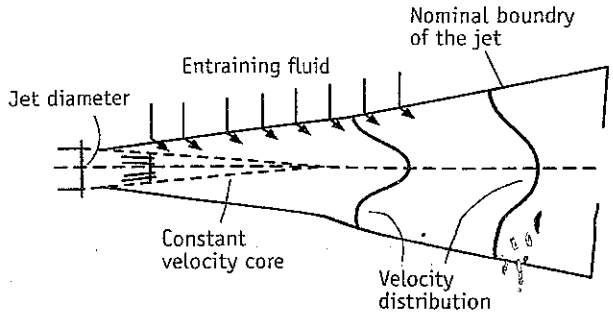


Figure 9-26. Mechanism of mixing in submerged circular jet mixer.

liquid is pumped through a small nozzle at uniform high velocity. The second liquid enters the tank at a low velocity. The fast moving liquid impinges on the slow moving liquid at high velocity. As the jet moves away from the orifice, the area of its influence decreases. The core of the jet is surrounded by an expanding turbulent jet, in which the radial velocity decreases with distance from the center-line of the jet.

When a rapidly moving liquid comes in contact with slow moving (or almost stationary) liquid, high velocity gradient will be developed at the boundary. As a result, strong shear stresses exist at the boundary, which induce mixing in two ways.

(1) The stresses tear off portions of the fast moving stream and send it off into the slower moving areas as vortexes or eddies. The shear stresses tear off eddies and generates considerable turbulence, which contributes to the mixing action.

(2) When a slow moving liquid enters the jet, the volume of jet increases and velocity decreases. This decreasing velocity causes the jet to expand. Thus shear develops which aids in mixing.

Enough time and space must be provided for the stream to blend thoroughly into the mass of fluid by the mechanism of entrainment.

Advantage : The power required for pumping is often sufficient to accomplish the mixing operation.

Flow Mixer or Line Mixer or Pipe Mixer

The constructions of a baffled pipe mixer and a chamber mixer are shown in Figure 9-27a and b, respectively. Liquids to be mixed are passed through the pipe. Mixing takes place mainly through bulk transport in the direction of flow. Placing certain devices, such as vanes, baffles, screws, grids and a combination of them, enhances the mixing efficiency. Little additional power supplied to pump the liquid itself accomplishes mixing.

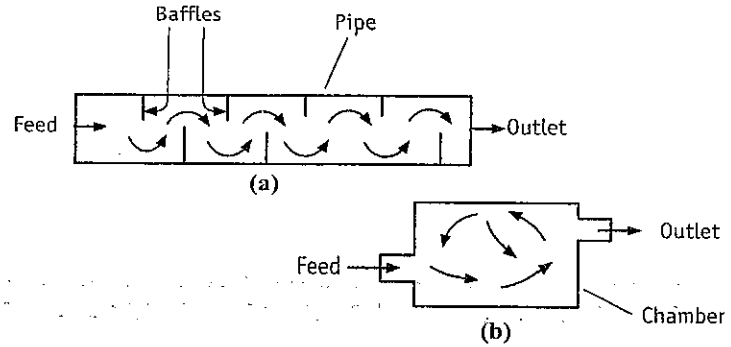


Figure 9-27. Flow pattern of continuous mixer or line mixer.

For an effective mixing, controlling the feed rate is essential. Suitable metering devices are employed. If input rate is difficult to control and fluctuations in the added proportions of the liquids are unavoidable, continuous mixing equipment of tank type is preferable, because hold-up of the liquids and back flow or recirculation is possible.

Uses : When large volume of liquids are to be mixed, flow mixers are used.

(a) Baffled pipe mixer with little back flow.

(b) Chamber mixer with flow induced recirculation and hold up.

Comment 9-10. Pipe mixers are used for mixing operation only. True or false. Explain.

Summary

Liquid-liquid mixing is a simple operation and homogeneous system can be easily achieved. Agitation induces the motion of liquids in a specified way. If the nature of liquid (to be mixed) is known, then mixing can be planned with ease. Liquid mixing promotes the heat transfer, crystallization, etc. The manufacture of liquid orals and parenterals involves mixing of liquids and solids to obtain solutions. The mechanisms of mixing are bulk transport, turbulent mixing, laminar mixing and molecular diffusion. Among these, bulk transport and turbulent mixing are the frequently operating mechanisms. Simultaneously more than one mechanism may operate. The mixing apparatus consists of a container (tank) and a mixing device. These are assembled for obtaining mixing. Variations in the designs of containers are observed, such as jacketed and container with baffles. The mixing devices are: propellers, turbines, paddles, etc. These give different flow movement such as tangential, radial and axial. Mixing involves combination movements. The flow patterns sometimes manifest into formation of vortex near the impeller shaft. The remedial measures are taken into prevent the formation of vortex. The equipment used for mixing of the liquids include, airjet mixer, jet mixer and flow mixer. Airjet mixer is batch type, while the latter two are continuous mixers.

QUESTION BANK

Each question carries one mark

Note : Encircle the alphabet which corresponds to the single best response.

1. When paddle is used for mixing of liquids, the flow pattern of a fluid is:
   A. axial and tangential
   B. axial or tangential
   C. radial and tangential
   D. radial or tangential
2. Which of these is NOT a mechanism for liquid mixing?
   A. Bulk transport mixing
   B. Laminar mixing
   C. Shear mixing
   D. Turbulent mixing

3. Which is the example of solid-liquid mixing?
   A. Aluminum hydroxide gel B. B. complex elixir
   C. Cod liver oil emulsion D. Ephedrine syrup
4. Baffles are fixed to the mixing vessel in order to promote:
   A. Bulk transport mixing B. Laminar mixing
   C. Shear mixing D. Turbulent mixing
5. Which one of the following mixing elements is used for mixing of solids in liquids (suspension)?
   A. Anchor B. Paddle
   C. Propeller mixer D. Turbine mixer

Each question carries 2 marks

1. Classy liquids based on their miscibility. Give one example in each case.
2. Enumerate the applications of liquid mixing.
3. Describe the mechanisms of liquid mixing
4. How are pipe mixers advantageous in liquid mixing?
5. What is meant by vortex? How is it prevented?
6. List the different impellers and indicate their flow pattern.

Each question carries 5 marks

1. Give the characteristics of a mixing impeller.
2. Describe the construction and working of agitator mixer with a suitable diagram.
3. Describe the turbine mixer with flow pattern.
4. Suggest a suitable mixer and its operation for mixing of viscous liquids.
5. Draw a neat-labeled diagram of mixing tank with accessories for efficient liquid mixing.
6. Describe the principle, working and advantages of a jet mixer.
7. What are flow components for liquids? Explain their role during mixing.
8. What are the reasons for vortex formation? What are the drawbacks of vortex? Suggest remedial measures for the preventing vortex formation.
9. Describe the liquid mixing step with critical quality attributes and process parameters.

Each question carries 10 marks

1. Describe the devices used for liquid mixing.

Section III—MIXING OF IMMISCIBLE LIQUIDS

Equipment

LEARNING OBJECTIVES

After reading this chapter, the reader should be able to:

- Describe the designs of industrial scale equipment for mixing of immiscible liquids along with working and uses.

Mixing of immiscible liquids is carried in pharmacy mainly in the manufacturing of emulsions. Along with immiscible liquids, surfactants (emulsifier) are added for producing of emulsions of adequate stability. Stabilizers are added further to increase the viscosity, so that stability is further increased. These components are added to the individual liquids based on their solubility. Such liquids are thoroughly sheared to obtain the desired (particle size) emulsion. The equipment used for the preparation of an emulsion is known as *emulsifier*. Generally a fine emulsion can be obtained and, therefore, equipment is also known as *homogenizer*.

Fine emulsion is prepared in two stages. In the first stage, coarse emulsion is prepared by using one of the following.

- wedge wood
- porcelain mortar and pestle
- mechanical blender
- milk-shake mixer
- hand homogenizer
- propeller in a baffled tank.

The equipment can be applicable to scaled up production size batches. The variables in the production are:

- Formulation type
- Equipment type
- Method of addition

The critical parameter for the emulsion process is the temperature.

- It is required to melt/dissolve the solids into liquid phase.
- Temperature is also a key during emulsification/dispersion
- Cooling is attempted to bring the temperature of emulsion to the ambient condition.

If no previous experience is available, then the following sequence of steps is used.

1. Melt all solid components of oil phase at 70 °C.
2. Bring the aqueous phase to 70 °C.

3. Maintaining at 70 °C through the dispersion step (shearing).
4. Cool to 40 °C slowly and packing.

The jacketed kettle is used for mixing and steam is used as the heating medium. If the viscosity of the emulsion is over 10,000 cps, scarped-surface agitator is desirable, in order to remove the liquid that may become too hot or cold. Designs are available that combine these mixers with a high shear rotor/stator mixer. This enables a single vessel to work within the entire viscosity range.

Sometimes, the above equipment directly gives fine emulsion. Otherwise, coarse emulsion is subjected to homogenization in the second stage to get fine emulsion by using one of the following.

- Silverson emulsifier
- Colloid mill
- Rapisonic homogenizer

Hence, these equipment are also known as homogenizers.

EQUIPMENT

Factors Influencing the Selection of an Emulsifier

Quantity of emulsion to be prepared : Batch wise or continuous operation.

Flow properties of liquids : Newtonian, plastic, pseudoplastic or dilatant.

Temperature maintenance : Mixing will be effective at high temperatures provided the material is stable.

Desired rate of cooling : If elevated temperatures are applied.

Some equipment used for the preparation of emulsions are described below.

Silverson Mixer—Emulsifier

Principle : Silverson mixer-emulsifier produces intense shearing force and turbulence by the use of high-speed rotors. This turbulence causes the liquids to pass through fine interstices formed by closely placed perforated metal sheets. Circulation of material takes place through the head by the suction produced in the inlet at the bottom of the head. Circulation of the material ensures rapid breakdown of the dispersed liquid into smaller globules.

Construction : The construction of a Silverson emulsifier is shown in the Figure 9-28. It consists of long supporting columns connected to a motor which give support to the head. The central portion contains a shaft, one end of which is connected to the motor and the other end is connected to the head. The head carries turbine blades. The blades are surrounded by a mesh, which is further enclosed by a cover having openings.

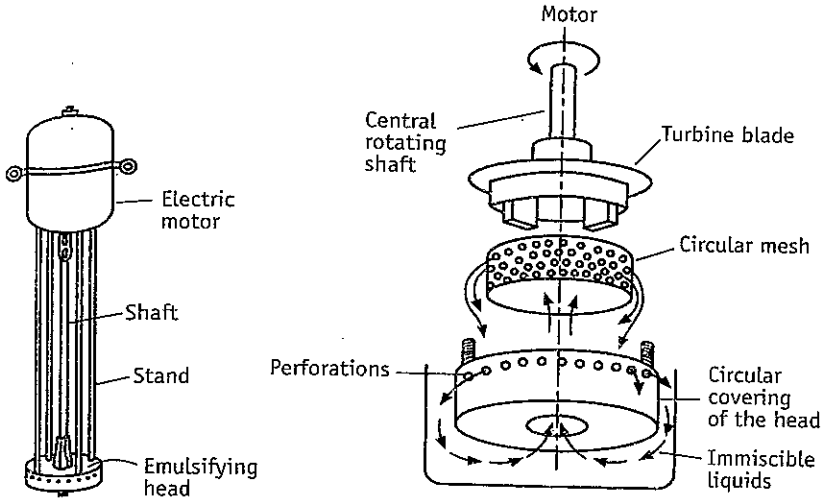


Figure 9-28. Silverson emulsifier.

Working : The emulsifier head is placed in the vessel containing immiscible liquids (or coarse emulsion) in such a way that it should get completely dipped in the liquid. When the motor is started, the central rotating shaft rotates the head, which in turn rotates turbine blades at a very high speed. This creates a pressure difference. As a result, liquids are sucked into the head from the center of the base and subjected to intense mixing action. Centrifugal forces expel the contents of the head with great force through the mesh and onto the cover (Figure 9-28b). As a result a fine emulsion emerges through the openings of the outer cover. The intake and expulsion of the mixture set up a pattern of circulation to ensure rapid breakdown of the bigger globules into smaller globules.

Uses : Silverson mixer is used for the preparation of emulsions and creams of fine particle size.

Advantages : (1) Silverson mixer is available in different sizes to handle the liquids ranging from a few millilitres to several thousand litres.

(2) It can be used for batch operations. It is also used for continuous operation by incorporating into a pipeline, through which the immiscible liquids flow.

Disadvantage : Occasionally, there is a chance of clogging of pores of the mesh.

Colloid Mill

Principle : Colloid mill is based on the principle that the coarse emulsion is intensely sheared in a narrow space between the fast moving rotor and stator for a short period to get a very fine emulsion.

Colloid mill is a mixer as well as milling equipment because size reduction is also simultaneously involved. The construction, working, advantages and disadvantages are discussed in the Chapter 3, Size Reduction.

Ultrasonic Emulsifiers—Rapisonic Homogenizer

Principle : When a liquid is subjected to ultrasonic vibrations, alternate regions of compression and rarefaction are produced in the liquid. Cavities are formed in the regions of rarefaction, which subsequently collapse in the regions of compression. This results in the generation of great forces for emulsification.

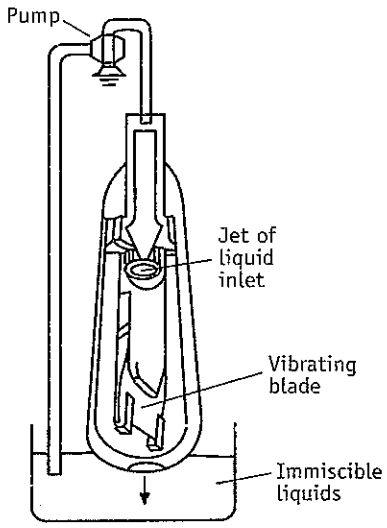


Figure 9-29. Rapisonic homogenizer.

Construction : The construction of a Rapisonic homogenizer is shown in Figure 9-29. It consists of a pump driven by a motor. It is connected with an inlet tube and outlet tube for the discharge of a fine emulsion. The homogenizer head consists of a flat jet for liquid inlet. Facing the jet, a thin blade is present with edges facing each other. This blade vibrates at its natural frequency of about 30 kilohertz.

Working : Coarse emulsion is pumped into Rapisonic homogenizer through one end of a tube. A powerful stream of liquid is forced through the jet. Liquid impinges on the blade causing it to vibrate. The streaming liquid deflects on either side alternatively with the result that oscillations above the sonic range are produced in the liquid. During this process, the emulsion experiences alternate regions of compression and rarefaction. In the regions of rarefaction, cavities are formed. Because of external pressure, the cavities collapse violently afterwards. Thus sufficient turbulence is created which is capable of causing dispersion of phases. Thus a coarse emulsion is converted into a fine emulsion.

Advantages:

(1) Rapisonic homogenizer can be used either for batch process by placing it in a tank or for continuous process by keeping in a pipeline. In a pipeline, the time of exposure is less for a given sample of liquid in one pass. So, mixing may be incomplete. To ensure complete mixing, liquids must be recirculated.

(2) It has the capacity to produce dispersed globules of one micron size.

(3) As this method is highly efficient to decrease globule size, reduced concentration of emulgents is sufficient.

(4) Its capacity of mixing liquids ranges from 20 to 500 L/min.

(5) In Rapisonic homogenizer, heat is not generated during mixing unlike colloid mill. Hence this is suitable for thermolabile substances.

Disadvantage : Rapisonic homogenizer is useful only with liquids of low viscosity.

Summary

The mixing of immiscible liquids involves two steps: formation of coarse emulsion initially and formation of fine emulsion finally. Each step requires separate equipment. The general terms, emulsifier or homogenizers, are used for the mixing of immiscible liquids. The formation of fine emulsions is obtained using Silverson mixer-emulsifier, colloid mill and ultrasonic homogenizer. Silverson emulsifier consists of high speed rotors, which produce intense shearing force and turbulence. Further liquids pass through fine interstices formed by closely placed perforated metal sheets. Circulation of the material repeatedly ensures rapid breakdown of the dispersed liquid into smaller globules. Silverson mixer is used for the preparation of creams and emulsions. In ultrasonic emulsifier, ultrasonic vibrations are created, i.e. alternate regions of compression and rarefaction in the liquid. Cavities subsequently collapse into the regions of compression. This results in the generation of greater forces for emulsification. Thus fine emulsions can be achieved.

Section IV—MIXING OF SEMISOLIDS

Equipment

LEARNING OBJECTIVES

After reading this chapter, the reader should be able to:

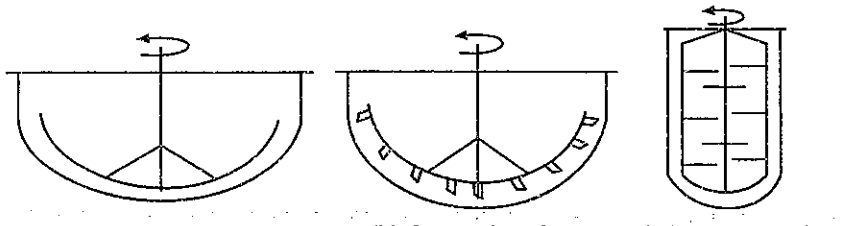
- Describe the designs of industrial scale equipment for mixing of semisolids along with working and uses.

Semisolid dosage forms include ointments, pastes, creams and jellies. While mixing such dosage forms, the material must be brought to the agitator or the agitator must move the material throughout the mixer. The mixing action includes combination of low speed shear, smearing, wiping, folding, stretching and compressing. A large amount of mechanical energy is applied to the material by moving parts. Sometimes, a part of the supplied energy appears as heat. The forces required for efficient mixing are high and consumption of power is also high. Hence, the equipment must be ruggedly constructed to tolerate these forces. Mixing equipment are also used for preparing tooth-pastes, pill masses and wet mass for granulation.

Some semisolids exhibit dilatant property, i.e. viscosity increases with increase in shear rates. Therefore, mixing must be done at lower speeds. The speed must be changed accordingly to thixotropic, plastic and pseudoplastic materials.

Anchor Agitator (mixer)

Anchor mixer is an agitator (mixing device) which has anchor shape (Figure 9-30a). The agitator moves slowly and produces low capability. It is useful for dispersion and emulsification without over shearing, aeration and heat transfer problems. The anchor agitator works up to 50 rpm and the sole function is to rotate the contents in a radial direction without



(a) Anchor agitator. (b) Scraped surface agitator. (c) Counter rotation agitator.

Figure 9-30. Mixing devices for semisolid preparations.

producing any significant shear. It functions at variable speeds. When the anchor agitator is built very close to the walls of the vessel, they are known as *swept-surface agitator* (Figure 9-30b).

Scraped-Surface Agitator

Flexible or movable blades are attached to the anchor, which is known as scraped-surface agitator. The flat blades are made of plastic, nylon and Teflon. The blades actually contact the inner walls of the vessel and scrap the liquid. This type has a distinct advantage. High viscosity materials do not flow away from the surface of the mixing vessel, unless the agitator is close proximity to the wall. The following procedure is adopted for semisolid mixing.

- Initially heat is supplied to the mixing vessel for maintaining at 40 and 80 °C.
- In the heat transfer process, the temperature at the sidewall is higher than the desired temperature in the batch (bulk). The prolonged higher temperature may have deleterious effects:
  - the drug may get decomposed
  - the excipients may get decomposed.
  - the product may actually stick to the side may burn at high heat.
- After mixing, the batch of immiscible liquids or semisolids is brought to the lower temperature. This also has disadvantages.
- The viscosity of the layer on the sidewall becomes high and virtually it is difficult to remove the liquid.
- The layer on the sidewall acts as an insulator, thereby reduces the effective heat transfer. Once this condition occurs, it is difficult to reverse.

Normally the layer of liquid residing on the wall for longer periods became too hot or too cold. This causes the problem of *burn on* or *freeze on*. This problem can be avoided by emptying scraped-surface agitation. Several designs of scraper blades are available.

1. Blades are arranged in rows.
2. Blades are fixed on both sides of an anchor.
3. Blades overlap making the anchor to complete revolution.
4. Blades are allowed to revolve in opposite directions. This prevents the buildup of product on the following edge.
5. Springs are included so as to force the blade against the wall.
6. Liquid is forced to flow onto the blade to bring it close to the wall by a suitable design.

Counter-Rotation Agitator

The counter-rotating agitator consists of a set of cross-bars that provide excellent blending. (Figure 9-30c).

1. Designs use the same motor, but turn on a pinion gears between two opposing bevel gears to provide rotation in opposite directions.
2. Designs have separate motors and their driving shafts, proving greater degree of flexibility.

A hallow shaft drive the anchor agitator and an additional shaft located inside the hallow shaft drives the inner cross bars.

EQUIPMENT

Classification of Equipment

Agitator mixers : Examples are sigma mixer and planetary mixer.

Shear mixers : Examples are triple roller mill and colloidal mill.

Sigma blade mixer and planetary mixer are described in the solid-solid mixing. Colloidal mill is discussed in the Chapter 3 'Size Reduction'. Triple roller mill is discussed here.

Selection of Mixing Equipment for Semisolids

(1) Physical properties of the materials - density, viscosity and miscibility.

(2) Economic considerations regarding processing - time required for mixing and power consumption.

(3) The cost of equipment and its maintenance.

Critical Quality Attributes – Semisolid Mixing

The CQAs, process parameters (PPs) and material attributes (MAs) are recorded in Figure 9-31. The semisolid mixing is considered in the context of production of ointments and pastes. The upstream operation must be the solubilization of ingredients into individual phases and the downstream operation is the packing into a suitable containers. Thus, semisolid mixing is the only step that imparts the desired quality attributes (Figure 9-31). The critical attributes are: assay, viscoelasticity and particle size distribution. Among these critical quality attributes, a few may be high risk or intermediate or low risk. Accordingly the high risk attributes are incorporated in the risk management systems and controlled strategy is applied.

The process parameters are several and optimization is a laborious process. Thus semisolid mixing is a complex process and always attempted for batch process. The parameters are: rate of shearing, temperature

program, using mixing duration, etc. These are controlled during mixing as standards with limits. The above are normally universal parameters, though changes are based on possible on the type of mixing system used.

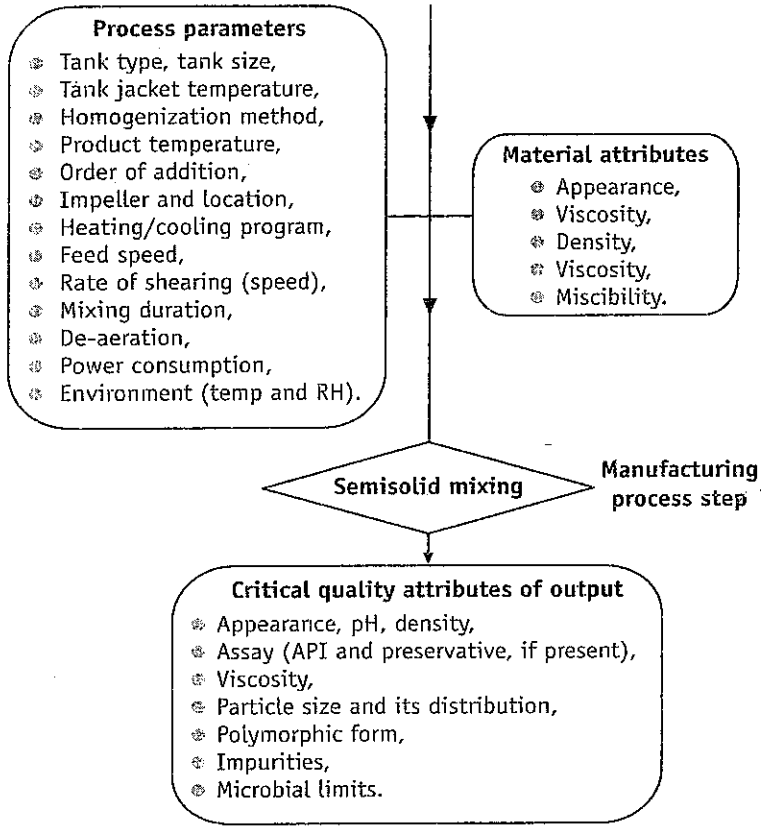


Figure 9-31. CQAs and process parameters for semisolid mixing in the production.

Triple Roller Mill

Principle : The differential speed and the narrow space between the rollers develop high shear over the material. This shear causes crushing of aggregates, particles and also distributes the drug uniformly through out the semisolid base.

Construction : The construction of a triple roller mill is shown in Figure 9-32. It consists of three parallel rollers of equal diameters. These are made up of hard abrasion resistant material, normally stainless steel. The rollers are mounted in a rigid framework horizontally. The pressure and gap between the rollers are independently adjustable. A hopper is arranged between the first two rollers. A scrapper is attached to the last roller.

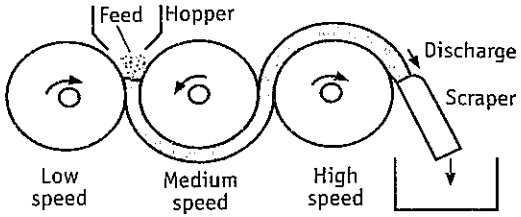


Figure 9-32. Triple roller mill.

Working : The gap between the last two rollers is adjusted to be less than the gap between the first two rollers. The rollers are rotated at different speeds. In practice, the first roller (receiving-roller) rotates at a slower speed compared to the second roller. Similarly second roller speed is less than that of third roller (discharge roller).

The feed is passed through the gap between the first and second rollers. The aggregates and particles are crushed and then abraded by the rubbing action of the rollers, which is developed due to different speeds of rotation. A film of appreciable thickness of the feed is produced. The material passes from slow rotating to fast rotating roller. Between second and third roller, the gap is small and produces a thinner film of feed. The speed of the third roller is increased to compensate the reduction of cross sectional area. In the thinning film, more crushing and more abrasion are developed.

Finally the scrapper removes the material completely from the last roller which can be collected immediately into the receiver or transported through a suitable conveyor.

Advantage : Triple roller mill is suitable for continuous processes. Extremely uniform dispersion is obtained.

Summary

The manufacture of ointments, pastes, creams and jellies involves the mixing of solids, liquids and semisolid ingredients. The mass is highly viscous and mixing is a difficult task and often includes a combination of low speed shear, smearing, wiping, folding, stretching and compression. In most of the situations, heat is supplied, so that mixing is facilitated in the molten state. Triple roller mill consists of three rollers, which rotate in different speeds, different temperatures, at different directions and the clearance between the rollers is narrow. This arrangement causes shear which crushes the drug uniformity throughout the semisolid base.

QUESTION BANK

Each question carries one mark

Note : Encircle the alphabet which corresponds to the single best response.

1. Which one of these is NOT a factor influencing the selection of a emulsifier?
   A. Conductivity of liquids
   B. Quantity of emulsion to be prepared
   C. Rheological properties of liquids
   D. Temperature maintenance
2. Select one of these as a suitable mixing element for emulsification.
   A. Marine type propeller B. Paddles
   C. Simple propeller D. Turbines
3. Silverson mixer is preferentially used for the preparation of:
   A. elixir B. emulsion
   C. mouth wash D. syrup
4. Mixing must be done at lower speed for semisolids, as some of them may exhibit one of the following rheological behaviour.
   A. Dilatant flow B. Plastic flow
   C. Pseudoplastic flow D. Thixotropy
5. Rapisonic homogeniser is useful only with liquids of:
   A. high viscosity B. intermediate viscosity
   C. low viscosity D. very high viscosity
6. The mechanism of mixing in Silverson mixer is:
   A. Convective mixing B. Laminar mixing
   C. Molecular diffusion D. Turbulent mixing
7. Mixing of semisolids is carried out using one of the following equipment.
   A. Double cone mixer B. Fluidised bed mixer
   C. Planetary mixer D. Cube mixer
8. Identify the statement NOT applicable to colloid mill.
   A. Colloid mill is not used for sterile products
   B. Colloid mill is not used to process dry materials
   C. Raise of the temperature can be reduced by cold water jacket
   D. Rotor and stator may be smooth surfaced or rough surfaced
9. Which of the following mixers has shearing as a mechanism of mixing?
   A. Planetary mixer B. Propeller mixer
   C. Sigma mixer D. Triple roller mill
10. Which one of the following mills generates heat during mixing?
    A. Colloid mill B. Rapisonic homogenizer
    C. Silverson mixer D. Triple roller mill

11. Which one of the following is considered as critical quality attribute for the product outcome from mixing of immiscible liquids?
    A. Assay
    B. Particle size distribution
    C. Viscosity
    D. Water washability
12. Which of the following is NOT used for mixing immiscible liquids?
    A. Colloid mill
    B. Rapisonic homogenizer
    C. Silverson mixer
    D. Triple roller mill
13. Silverson emulsifier shears the material through one of the following actions?
    A. Centrifugal
    B. Suction
    C. Turbine
    D. Ultrasonic vibrations
14. Which one of the following is NOT a suitable equipment for mixing of semisolids?
    A. Colloid mill
    B. Hammer mill
    C. Roller mill
    D. Sigma mixer
15. Which one of the following sets is closely related to mixing of semisolids?
    A. Bulk transport, turbulent mixing, laminar mixing and molecular diffusion
    B. Convective mixing, shear mixing, diffusive mixing and micro-mixing
    C. Newtonian, plastic, compression and rarefaction
    D. Smearing, folding, stretching and compressing
16. Identify WRONG feature of a roller mill.
    A. Gap between first two rollers is less than the last two rollers
    B. Rollers are rotated at different speeds
    C. Rollers are made of a hard abrasion-resistant material
    D. Scrapper is placed close to the last roller
17. Planetary mixer is used for mixing of one of the following systems?
    A. Immiscible liquids
    B. Miscible liquids
    C. Semi-solids
    D. Solid-gas
18. Identify the WRONG disadvantage of semisolids mixing equipment.
    A. Dead spots are formed in ribbon blender
    B. Planetary mixer is for batch operation
    C. Sigma mixer works at a fixed speed
    D. Triple roller mill is not used for continuous process

Each question carries 2 mark

1. Suggest suitable mixing equipment for semisolids.
2. List the factors influencing the selection of an emulsifier.
3. Describe the differences in mixing of immiscible liquids and semisolid liquids.

4. Describe the event 'burn' on or 'freeze' on with relevant reasons for the same.

Each question carries 5 marks

1. Describe the construction and working of the Silverson emulsifier with the help of a neat diagram.
2. Describe the construction and working of the rapisonic homogenizer.
3. Write the principle of a mixer suitable for mixing of solids and semisolids.
4. Describe the semisolid mixing process step with critical quality attributes and process parameters.
5. Explain the advantages and disadvantages of anchor blade in the semisolid mixing with relevant modifications.
6. Explain the semisolid mixing in terms of process parameters and critical quality attributes.

CHAPTER 10

Filtration

Mechanisms of Filtrattion
Theories of Filtration
Factors Influencing Filtration
Filter Media and Filter Aids
Classification of Filtration Equipment
Laboratory Scale Filtration — Methods
Industrial Equipment
Selection of Filtration Equipment

LEARNING OBJECTIVES

After reading this chapter, the reader should be able to:

- Understand the process of filtration with relevant mechanisms of separation and applications.
- Explain the theories of filtration illustrating the principles for developing the equations.
- Review the factors influencing the filtration including filter aids and filter media for applications in the production.
- Highlight the classification of filtration equipment.
- Describe the principle, construction, working and uses of different types of equipment.
- Select filtration equipment for obtaining desirable product.

Filtration may be defined as a process of separation of solids from a fluid (liquid or gas) by passing the same through a porous medium that retains the solids, but allows the fluid to pass through.

The suspension to be filtered is known as *slurry*. The porous medium used to retain the solids is known as *filter medium*. The accumulated solids on the filter are referred to as *filter cake*, while the clear liquid passing through the filter is *filtrate*.

Process of Filtration

A typical filtration operation is shown in Figure 10-1. The pores of the filter medium are smaller than the size of particles to be separated. Filter medium (e.g. filter paper or muslin cloth) is placed on a support (a

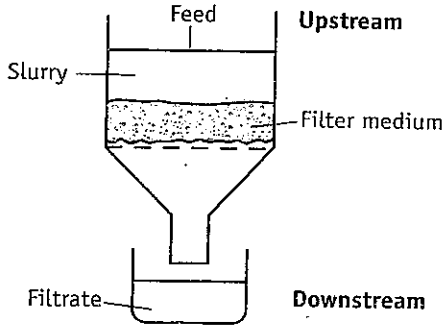


Figure 10-1. Principle of filtration.

mesh). When slurry (feed) is passed over the filter medium, the fluid flows through the filter medium by virtue of a pressure difference across the filter. Gravity is acting on the liquid column. Therefore, solids are trapped on the surface of the filter medium.

Once the preliminary layer of particles is deposited, further filtration is brought about wherein the filter medium serves only as a support. The filter will work efficiently only after an initial deposit. In an industrial scale, large quantities of suspensions are mechanically handled. After a particular point of time, the resistance offered by the filter cake is so high that virtually filtration is stopped. For this reason, a positive pressure is applied on the filter cake (upstream) or negative pressure (suction) is applied below the filter medium (downstream).

Clarification

Clarification is a separation process of solid from the liquid, when solids are present in very low concentration, i.e. not exceeding 1 % w/v.

Clarification is generally employed when contaminating material is finely divided, amorphous or colloidal in nature. The solids tend to plug the filter medium. In such cases, filter aids are used. Several other processes having similar mechanism are: discolouration, decantation, collation, expression, etc. Clarification of solutions is intended to:

- Eliminate unwanted solids (contaminants) present in small quantities.
- Removal of foreign organic particles (size < 0.3 μm) for parenteral use.
- Removal of microorganisms from solutions to prepare sterile products.
- Remove bioburden from the effluents.

For clarification *thick media* is used for separation. Pore size is an important parameter.

Applications

Production of sterile products : Air is filtered through HEPA filters (high efficiency particulate air filters) or laminar air-bench to obtain sterile air, which maintains good environment prior to and during manufacture of sterile products.

A solution is passed through a bacteria proof filter in order to obtain sterile solution, particularly when heat sterilisation is not suitable on account of thermolabile nature of the contents. In case of sterile products, particles as small as 0.2 μm should be removed, which includes the bio-burden of fungi, bacteria, etc.

Similar facilities are required for the production of antibiotics by fermentation, recombinant technologies of biological products and vaccines.

Production of bulk drugs : Solids of intermediates and finished products are separated from the reaction mixture by filtration technique. By this method, impurities can be removed.

Production of liquid oral formulations : Filtration is an essential step in the production of liquid oral solutions for obtaining clear solutions (clarification).

(a) Dewaxing of oils. Waxes are removed from oil by filtration under reduced temperature as an attempt for decontamination.

(b) Removing suspended oils from aqueous solutions. E.g. aromatic waters, syrups, elixirs, eye drops, etc.

(c) Removing of undesirable solids, which interfere with the transparency of the liquids. E.g. honey and fruit juices.

(d) Clarifying the potable water.

Effluent and waste water treatment : Waste solids must be separated from the waste liquid prior to its disposal. Sometimes, the soluble components are precipitated and then separated by filtration.

Comment 10-1. Clarification is faster for given nature of feed. Explain.

MECHANISMS OF FILTRATION

The mechanism whereby particles are retained by a filter is significant only in the initial stages of filtration. Some of the mechanisms are:

Straining : Similar to sieving, i.e. the particles of larger size cannot pass through the smaller pore size of the filter medium.

Impingement : Solids having the momentum move along the path of streamline flow and strike (impinge) the filter medium. Thus, the solids are retained on the filter medium.

Entanglement : Particles become entwined (entangled) in the mass of fibres (of cloth with a fine hairy surface or porous felt) due to smaller size of particles than the pore size. Thus the solids are retained within the filter medium.

Attractive forces : Solids are retained on the filter medium as a result of attractive forces between particles and filter medium, as in case of electrostatic precipitation.

In practice, filtration may combine various mechanisms.

Types of Filtration

Based on the mechanism, two types of filtration are broadly identified.

Surface filtration (Screen filtration) : It is a screening action by which pores or holes of the medium prevent the passage of solids.

The mechanisms, straining and impingement are responsible for surface filtration. For this purpose, plates with holes or woven sieves are used (Figure 10-2). Its efficiency is defined in terms of mean or maximum pore size.

Depth filtration : In this process, slurry penetrates to a point where the diameter of solid particles is greater than that of the tortuous void or channel.

Depth filtration is aided by the mechanism entanglement. The contaminants move through the fibre matrix and eventually will collide with fibres and separate from the medium. The solids are retained with a gradient density structure by physical restriction or by adsorption properties of the medium (Figure 10-2). It is extensively used for the removal of small amounts of contaminants from relatively large volumes of liquids (clarification). These are also used for prefiltering pharmaceutical solutions, e.g. ceramic filters and sintered (bed) filters.

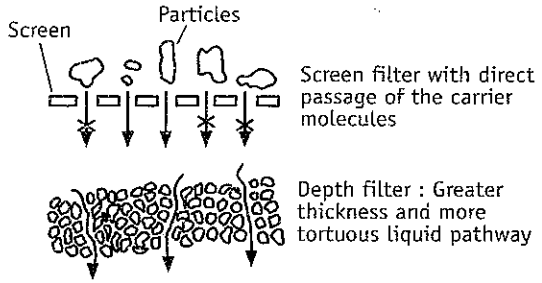


Figure 10-2. Types of filtration.

Depth filtration promotes high dirt-load capacity of contaminants. Depth filters are utilized for coarse particle removal, polishing the filtrate. The particles retained are a few hundred times smaller than the dimensions

of the passage through the medium. Such filters are not absolute and need to be designed specially for an absolute particle diameter, closely related to the pore size, so that sharp division between particles which pass the filter and those that are retained can be defined.

A special case of depth filtration is the sheet filtration, in which the slurry is passed through a series of pads mounted endwise to the flow of fluids. The pads commonly consist of a mixture of asbestos fibres embedded in cellulose.

The differences between surface and depth filtrations are given in Table 10-1.

TABLE 10-1

Differences Between Surface and Depth Filtration

Surface filtration	*Depth filtration*
The size of the particles retained is slightly higher than the mean pore size of the medium.	The size of the particles retained is much smaller than the pores through which fluid passes.
Mechanical strength of the filter medium is less, unless it is made of stainless steel.	Mechanical strength is high.
It has low capacity.	It has high capacity.
The size of the particles retained is more predictable.	The size of the particles retained is less predictable.
Equipment is expensive because it should require ancillary equipment such as edge clamps, which should have much finer tolerances.	Cheaper because ancillary equipment is not required.
Example is cellulose membrane filter.	Examples are ceramic filters and sintered (bed) filters.

Cake filtration : This filter consists of a coarse woven cloth through which a concentrated suspension of rigid particles is passed so that they bridge the holes and form a bed.

The concentration of suspended solids is usually 3 to 20 %. The cloth or septum is only a support and actual filtration takes place by the solids deposited as a cake. In cake filtration, filter aids are added to the slurry and allowed to pass through the filter bed. These solids are responsible for the formation of cake. These penetrate the septum (pores of medium) and form an effective cake. This requires a certain time, until which the initial filtrate would be cloudy and hence is recycled for effective filtration. The physical properties of cake (filter aids) decides the effectiveness of filtration. In cake filtration, washing and partial drying or dewatering often are integral parts of the processes. The solids, the filtrate or both may be

wanted. The cloth may be ineffective when the holes are likely to be much larger than the particles to be removed. The particles will be held back, while liquid passes through the small interstices. E.g. filter cake made from diatomite (100 μm). This cake can remove submicrometer colloidal particles with high efficiency.

THEORIES OF FILTRATION

The theories of filtration are essentially related to two aspects namely:

- Flow of liquid through a porous media – cake filtration and clarification.
- Retaining solids – clarification, depth filter.

The flow of a liquid through a filter follows the basic rules that govern the flow of any liquid through the medium offering resistance. The rate of flow may be expressed as:

$$\text{Rate} = \frac{\text{driving force}}{\text{resistance}} \qquad ...(1)$$

The rate of filtration may be expressed as volume (litres) per unit time (dv/dt). The driving force is the pressure differential between the upstream and downstream of the filter. The resistance is not constant. It increases with an increase in the deposition of solids on the filter medium. Therefore filtration is not a steady state.

The rate of flow will be greatest at the beginning of the filtration process, since the resistance is minimum. Once the filter cake is formed, its surface acts as filter medium and solids continuously deposit adding to the thickness of the cake. The resistance to flow is related to several factors (Figure 10-3).

$$\text{Resistance to movement} = \frac{\text{pressure upstream} - \text{pressure downstream}}{\text{length of capillaries}} \qquad ...(2)$$

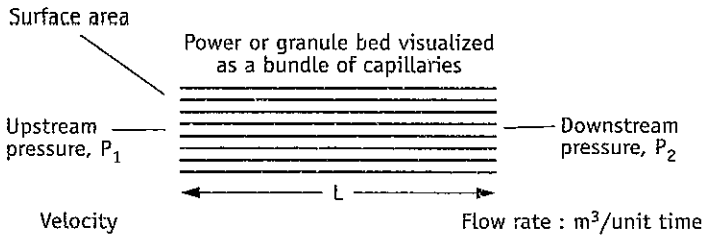


Figure 10-3. Filtration process-parameters.

Poiseuille's Equation

Poiseuille considered that filtration is similar to the streamline flow of a liquid under pressure through capillaries. Poiseuille's equation is:

$$V = \frac{\pi \Delta P r^4}{8L\eta} \quad ...(3)$$

where V = rate of flow, i.e. volume of liquid flowing in unit time, m^3/s (l/s)
ΔP = pressure difference across the filter, Pa
r = radius of the capillary in the filter bed, m
L = thickness of the filter cake (capillary length), m
η = viscosity of the filtrate, Pa·s

If the cake is composed of a bulky mass of particles and the liquid flows through the interstices (correspond to a multiplicity of capillary tubes), then the flow of liquids through these may be expressed by Poiseuille's equation.

Darcy's Equation

Darcy's law assumes that the capillaries found in the filter are highly irregular and nonuniform. Therefore, if the length of a capillary is taken as the thickness of the bed, a correction factor for radius is applied so that the rate equation is closely approximated and simplified. The factors influencing the rate of filtration has been incorporated into an equation by Darcy, which is:

$$V = \frac{KA\Delta P}{\eta L} \quad ...(4)$$

where K = permeability coefficient of the cake, m^2
A = surface area of the porous bed (filter medium), m^2

Other terms are same as shown in equation (3). The term K depends on the characteristics of the cake, such as porosity, specific surface area and compressibility.

Permeability may be defined quantitatively as the flow rate of a liquid of unit viscosity across a unit area of cake having unit thickness under a pressure gradient of unity.

This model relates not only to filter beds or cakes but also applies to other types of depth filter. Equation (4) is valid for liquids flowing through sand, glass beads and various porous media. Darcy's equation is further modified by including characteristics of K by Kozeny-Carman.

Kozeny-Carman Equation

Poiseuille's equation is made applicable to porous bed, based on a capillary type structure by including additional parameters. The resultant equation for filtration is Kozeny-Carman equation.

$$V = \frac{A}{\eta S^2} \cdot \frac{\Delta P}{KL} \cdot \frac{\varepsilon^3}{(1-\varepsilon)^2} \quad ...(5)$$

where ε = porosity of the cake (bed)
S = specific surface area of the particles comprising the cake, m^2/m^3
K = Kozeny constant

Other terms are same as shown in equations (3) and (4). The Kozeny constant is usually taken as 5. The effect of compressibility of the cake on flow rate can be appreciated from equation (1), since the flow rate is proportional to $\varepsilon^3/(1-\varepsilon)^2$. A 10 % change in porosity can produce almost 3-fold change in V.

Limitations of Kozeny Carman equation : Kozeny Carman equation does not take into account of the fact that the depth of the granular bed is lesser than the actual path traversed by the fluid. The actual path is not straight throughout the bed, but it is sinuous or tortuous.

Retaining Solids – Clarification

For clarification (depth filter and cake filter), high permeability and filtration rate are expected, but it opposes particle retention. Both are desirable and a balance must be made. Sintered or loose articles provide accurate control of particle size, specific surface and porosity. Analysis of permeability of clarification can as well be applied to general filtration. Since particle size distribution is wide, extreme sizes and shapes offer difficulties, if fibrous filter medium is used. Thus permeability as well as solid retention are evaluated and both are expected to be high.

FACTORS INFLUENCING FILTRATION

A simple straining process does not provide a complete description of how particles are removed from a suspension. The particles are exposed to a number of forces including gravity or electrical fields. Some of the factors influencing the filtration are:

(1) Properties of the liquids—density, viscosity and corrosiveness.
(2) Properties of the solids—particle shape, particle size, particle charge, density, particle size distribution, rigidity or compressibility of the solid under pressure and tendency of particle to flocculate or adhere together.
(3) Proportion of solids in the slurry—rate at which the filter cake is formed, especially in the early stages of the filtration.
(4) Objectives—whether the solids or the liquid or both are to be collected.
(5) Temperature of the suspension.

Surface Area of the Filter Medium

According to equation (5), rate of flow of filtrate flowing through the filter is inversely proportional to the specific surface of the filter bed. On the other hand, if the surface area of the filter medium is considered, the rate of filtration is directly proportional to the surface area of the filter medium (equation 4). Hence, the rate can be increased either using a larger filter or connecting a number of small units in parallel. For example, plate and frame filter press works on the principle of connecting the units in parallel. Pleating the filter paper or using a pleated funnel increases the effective surface area for filtration.

Pressure Drop Across the Filter Medium

According to equation (5), rate of filtration is directly proportional to the overall pressure drop across filter medium and filter cake. The pressure drop can be achieved in a number of ways:

Gravity (filter) : A simple method of obtaining a pressure difference is maintaining a head of slurry above the filter medium. The pressure developed depends on the density of the slurry. As a rough guide, a head of 10 m of water creates a pressure difference of 100 kilopascals.

Applying pressure (filter) : The most common method of obtaining a pressure difference is applying pressure on the surface of the slurry, i.e. pumping the slurry onto the filter.

The pressure difference obtained by this method is greater than that is achieved by reduced pressure. Industrial plant may be operated at pressure up to 1500 kilopascals. However, in the early stages of filtration, pressure difference should be less. This is to prevent the pores of the filter medium from clogging or plugging, which subsequently increases resistance to the flow. Pressure filters can be used for batch type operation and continuous pressure filters are not common and expensive.

Reducing pressure (vacuum filter) : The pressure underneath the filter medium may be reduced below atmospheric pressure by connecting the filtrate receiver to a vacuum pump. This creates a pressure differential across the filter. This factor has limited applications, because the pressure difference of about 100 kilopascals may be achieved. Reduction of pressure lowers the boiling point of liquids so that it is possible for the filtrate to boil in the receiver. Apart from the loss of liquid, the vapour may damage the vacuum pump.

Advantage of this method is safety. If a part of the equipment fails, it will collapse and not explode. Therefore, this method is commonly applied in a laboratory, where the apparatus is usually made of glass. However, in the industrial scale, the plant is usually constructed with a metal that is able to withstand high pressure.

Centrifugal force : Centrifugal force could replace the gravitational force and is used to increase the rate of filtration. The principle behind centrifugation is discussed separately in the chapter 11.

Viscosity of Filtrate

According to equation (5), rate of filtration is inversely proportional to the viscosity of the fluid. The viscosity of the liquid, not the slurry is important, since the resistance to flow occurs as the filtrate flows through the filter cake.

Raising the temperature of the liquid, which lowers the viscosity, may increase the rate of filtration. This is not practicable, if thermolabile materials are involved or if filtrate is volatile. Another alternative to decrease the viscosity is to dilute the filtrate. In this case, it is important to ensure that by doubling the volumes, the rate must be more than double, which should indicate the advantage.

In brief, surface area and pressure differences are the two factors, which are applied, in industrial practice. According to equation (5), other factors such as porosity also influences the rate of filtration. These are discussed below with filter aids.

Comment 10-2. What are the factors related to the feed relevant for the filtration?

Comment 10-3. What are the differences between pressure filtration and vacuum filtration?

FILTER MEDIA AND FILTER AIDS

Filter Media

The *filter medium* acts as a mechanical support for the filter cake and is also responsible for the collection of solids.

Characteristics : Filter medium should have the following characteristics.

(1) It should have sufficient mechanical strength.
(2) It must be inert, for example, it should not show chemical or physical interaction.
(3) It should not absorb dissolved material.
(4) It should allow maximum passage of liquid, while retaining the solids. It means that it must offer low resistance to flow. The resistance offered by the filter medium is not significant in large scale operations and can be neglected.

The magnitude of the resistance of the filter medium will change due to the layers of solids deposited earlier, which may block the pores or may form bridges over the entrances of the channels. Therefore, the pressure

should be kept low at the beginning to avoid the plugging of the pores. The usual procedure is to filter at constant rate by increasing the pressure as necessary. When normal working pressure is reached, it is maintained. On continued filtration, the thickness of the cake further builds up and hence the rate of filtration decreases. When the rate is uneconomical, filtration is stopped. The filter cake is removed and filtration is restarted.

Materials : The following materials are used as filter media.

(1) ***Woven materials such as felt or cloth*** **:** Woven material is made of wool, cotton, silk, glass, metal or synthetic fibres (rayon and nylon. Synthetic fibres have greater chemical resistance than wool and cotton, which are affected by alkali and acid, respectively. The choice of the fibre depends on the chemical reactivity with the slurry.

(2) ***Perforated sheet metal*** **:** For example stainless steel plates have pores which act as channels as in case of metafilter (edge filter).

(3) ***Prefabricated porous solid unit*** **:** Porous solids prefabricated into a single unit are being increasingly used for its convenience and effectiveness. Sintered glass, sintered metal, earthenware and porous plastics are some of the materials used for the fabrication. Terylene is useful filter medium for acid filtration.

(4) ***Membrane filter media*** **:** Cartridge units are economical and available in pore size of 100 μm to even less than 0.2 μm. These can be used either as surface cartridges or depth type cartridges.

(a) *Surface type cartridges* : These are corrugated and resin treated papers. These are used in hydraulic lines. Ceramic cartridges are advantageous in cleaning for reuse by back flushing or firing. Porcelain filter candles are used for sterile filtration.

(b) *Depth type cartridges* : These are made of cotton, asbestos or cellulose. These are disposable items, since cleaning is not feasible.

(5) ***Bed of granular solid built up on a supporting medium*** **:** In some processes, a bed of graded solids may be formed to reduce the resistance to the flow. Typical examples of granular solids are gravel, sand, asbestos, paper pulp and keiselguhr. The choice of solids depends on the size of the solids in the process. These are obtained using filter aids.

Filter Aids

Filter aid forms a surface deposit which screens out the solids and also prevents the plugging of the supporting filter medium.

Justification : The objective of the filter aid is to prevent the medium from becoming blocked and to form an open, porous cake, hence, reducing the resistance to flow of the filtrate.

(a) Usually, low resistance is offered by the filter medium itself. But as the layers of solid built up, the resistance will be increased. The cake may become impervious by blocking of the pore in the medium. Flow rate is inversely proportional to the resistance of the solid cake.

(b) Slimy or gelatinous material and highly compressible substances form impermeable cakes. The filter medium gets plugged and the flow of filtrate stops.

Characteristics : The important characteristics of the filter aids are:

(a) Chemically inert to the liquid being filtered and free from impurities.

(b) Low specific gravity, so that filter aids remain suspended in liquid.

(c) Porous rather than dense, so that cake can be pervious.

(d) Recoverable.

Disadvantages : The filter aids remove the coloured substances by absorbing them. Sometimes active principles such as alkaloids are adsorbed on the filter aid. Rarely, filter aids are a source of contaminants such as soluble iron salts, which can provoke degradation of sensitive ingredients. Liquid retained in the pores of the filter cake is lost in the manufacturing process.

Examples of filter aids are:

Keiselguhr	Talc	Charcoal	Asbestos
Paper pulp	Bentonite	Fullers earth	

Activated charcoal is used for removal of organic and inorganic impurities. Kieselguhr is a successful filter aid and as little as 0.1 % can be added to the slurry. The rate of filtration is increased by 5 times or more, at the above concentration, though the slurry contains 20 % solids.

Handling of filter aids : Filter aids are mostly used for clarification processes, i.e. where solids are discarded. Different flow rates can be achieved depending on the grade of the aids.

- Low flow rate (fine solids)—Fine grade filter aids—mainly intended for clarity.
- Fast flow rate (coarse solids)—coarse grade filter aids—acceptable filtrate.

The filter aid can be employed in either one or both ways.

(1) Firstly, a pre-coat is formed over the medium. For this purpose, a suspension of the filter aid is filtered to give a coating up to 0.5 kg per metre square.

(2) Secondly, a small proportion of filter aid (0.1 to 0.5 % of total batch weight) is purposely added to the slurry. So the filter cake has a porous structure and filtration can be efficient. The filter aid of 1 to 2 parts per each part of contaminant is mixed in the feed tank. This slurry is recirculated through the filter until a clear filtrate is obtained. Filtration then proceeds to completion. The body mix method minimizes equipment requirements and cross contamination potentials.

Comment 10-4. Why coagulants are added to the slurry before proceeding for filtration?

Comment 10-5. Filter aids increase the rate of filtration by many times compared to the filter medium. Explain.

Comment 10-6. Is there any relevance of amount of filter aids used in filtration? Explain

CLASSIFICATION OF FILTRATION EQUIPMENT

Equipment are classified based on the application of external force.

(1) *Pressure filters*—Plate and frame filter press and metafilter.

(2) *Vacuum filters*—Filter leaf.

(3) *Centrifugal filters*—These are discussed in the centrifugation chapter.

Classification based on the operation of the filtration.

(a) *Continuous filtration*—Discharge and filtrate are separated steadily and uninterrupted.

(b) *Discontinuous filtration*—Discharge of filtered solids is intermittent. Filtrate is removed continuously. The operation should be stopped to collect the solids.

Classification based on the nature of filtration.

(a) *Cake filters*—Remove large amounts of solids (sludge or crystals).

(b) *Clarifying filters*—Remove small amounts of solids.

(c) *Cross-flow filters*—Feed of suspension flows under pressure at a fairly high velocity across the filter medium.

These classifications methods help in selecting filtration equipment.

LABORATORY SCALE FILTRATION — METHODS

For laboratory work on filtration, paper, porcelain and sintered glass (or sintered metal) are employed.

Filter Paper and Funnel

Filter paper of different purities, porosities and textures are available. A majority of pharmaceutical operations use white filter paper. Paper of poor quality may contain impurities such as chlorides, iron, ash on ignition and soluble impurities. However, the commercial grades are washed with hydrochloric acid and hydrofluoric acid followed by water. Funnel is used for supporting the filter paper. The funnels are made of glass, porcelain or plastic.

Buchner Funnel and Filter Paper

Ordinary Buchner funnel consists of a cylindrical porcelain funnel carrying a fixed, flat and perforated plate. It is fitted to the neck of the thick water filtering flask (Buchner flask or suction flask), by means of a rubber stopper (or rubber cone). This assembly is attached to a safety bottle and the latter is attached to the rubber (pressure) tubing to a filter pump (Figure 10-4).

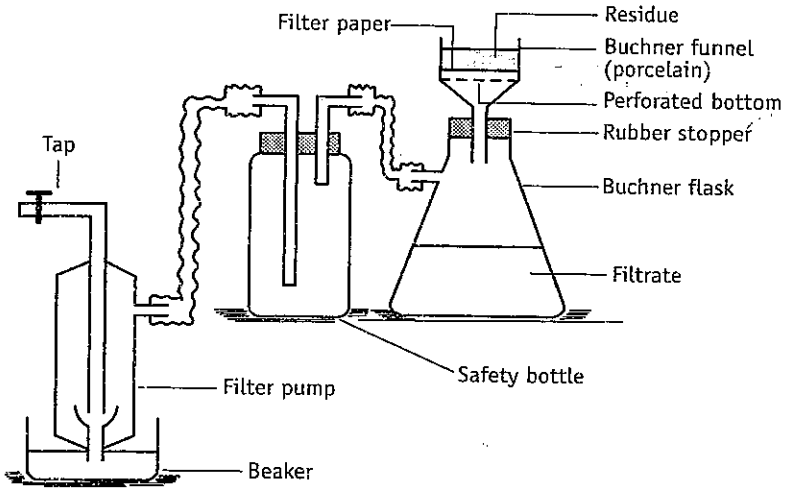


Figure 10-4. Laboratory method of filtration using Buchner flask and funnel.

A filter paper is selected, trimmed to the size and is placed in the Buchner funnel. It covers the entire perforated plate. The diameter should be slightly less than the inside diameter of the funnel. The filter paper is moistened with a few drops of clear supernatant liquid. Much of the supernatant liquid is poured initially into the funnel and filtered. Then, the bulk of the residual slurry is transferred. This procedure is often quicker than initially bringing all the solids into suspension and pouring it directly into the filter.

The filtration of very finely divided suspended solids is often very tedious, as the filter paper pores get clogged. In such cases, a suitable filter aid is added to the suspension to overcome the problem.

Sintered Glass Filter

Sintered glass filter is a glass funnel in which porous disc is fitted. Sinter is a German name for a porous mineral precipitated in crystalline form from mineral water. The glass is made by sintering a bed of granules of borosilicate glass *in situ*. This is then fitted into the funnel (Figure 10-5). Such an assembly can be fitted to the filtration unit. Sintered glass filters are available in a wide variety of porosities and specifications for quality. The porosities of these filters are indicated by numbers.

Grade 3, 4 – used for clarification of non-sterile solutions.

Grade 5 – used for sterile filtration, eye drops, etc.

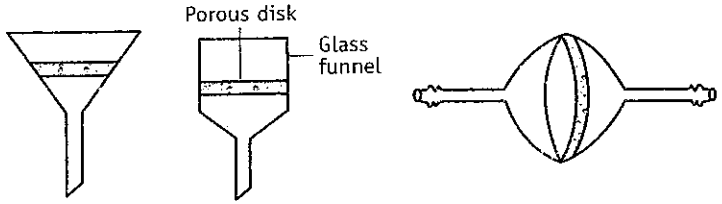


Figure 10-5. Laboratory method of filtration using sintered filters.

Uses : Sintered glass filters are used for sterile filtration for pharmaceutical solutions containing thermolabile substances and gases including air. These can be used to filter corrosive liquids and solutions containing oxidising substances. These can be repeatedly steamed or hot sterilised.

Advantages : Sintered glass filters are easily cleaned by passing a stream of water through the filter in the reverse direction. These do not yield fibres or impart alkali to filtrate. Adsorption of components of filtrate is low. Liquid retention through this filter is also low.

Disadvantages : Sintered glass filters are expensive and fragile. Hence, these cannot be built in large sizes. These offer smaller surface area for filtration. Micro-organisms tend to grow on the filter, if left in contact for more than 18 hours.

Seitz Filter

Seitz filter consists of a pad of compressed asbestos as a filtering medium (Figure 10-6). Typical Seitz filter pads are about 2 mm thick and offered in a range of size, down to well below one micrometer diameter. The finest pore size gives almost perfect filtration and retains small viruses. For industrial use, somewhat thicker pads are made to be fitted into specially made plate and frame filter press. The mechanism is similar to depth filtration.

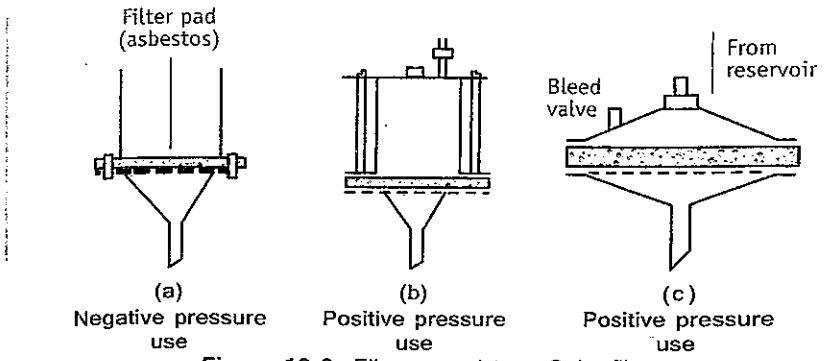


Figure 10-6. Fibrous pad type Seitz filters.

Uses : Seitz filters are useful for sterile filtration (Seitz EK asbestos pad). Finest pads give almost perfect filtration of small volumes. Viscous solutions can also be filtered. These are used for air filtration. Surface charging and electrostatic attractions have significant influence in removing particles. If the air is dry, these have greater the influence of filtration.

Advantages : Pads are expensive and filtration is rapid with fewer tendencies to clog. These are better than ceramic and Sintered glass filters for viscous solutions.

Disadvantages : Seitz filters are pliable and fragile when wet and must be supported on a perforated metal, plastic or galls disc. A new pad must be used for each filtration in order to avoid residues of previous filtration. Fibrous pads are not suitable for sterilising products containing alcohol or oil.

Membrane Filter

Principle : Membrane filter acts like a sieve and the particulate matter is retained on the surface of the membrane.

Construction : Membrane filters are made using cellulose acetate, cellulose nitrate or mixed cellulose esters. Membrane filters are supported on a rigid base of perforated metal, plastic or coarse sintered glass (as in case of fibrous pad filters). These have got high retention characteristics due to pore size, high dielectric constant and surface sensitivity. These are available with different pore sizes.

Pore size, mm	*Utility*
0.010 to 0.10	remove virus particles from air and water.
0.03 to 0.65	remove bacteria.
0.8, 1.2, 3.0 to 5.0	particle sizing and purifying aerosol, radioactivity.

If the solution to be filtered contains a considerable quantity of suspended solids, preliminary filtration through a suitable depth filter avoids clogging of the membranes.

Uses : Disc membranes with nutrient broth are used for studying the growth of micro-organisms and colony counts. Membrane filters can be autoclaved and used for sterile filtration.

Advantages : Membrane filtration is rapid. Adsorption is negligible and is not prone to fibre contamination or do not impart alkali to the filtrate. These are available as disposable items and hence cross-contamination is prevented. Bacterial growth on the membranes is not observed, even though prolonged filtration takes place. In order to prevent curling, the membranes are packed in holders or packed between thick filter pads. Pre-sterilised hermetically sealed packs (with ethylene oxide or ionising radiations) are supplied.

Disadvantages : The most refined grades are expensive and mostly used for laboratory tests, such as collecting micro-organisms for microscopic examination. Membrane filters are brittle when dry and can be stored indefinitely in the dry state, but are fairly tough when wet. Filters may get clogged. Ordinary types are less resistant to solvents such as chloroform, polyethylene glycols, certain alcohols, dimethylformamide, esters and ketoses.

INDUSTRIAL EQUIPMENT

In the bulk drug industry, solid is the desired product. Its size, physical properties and purity are important. These factors should be considered, while selecting the equipment and operating conditions. Some of them are:

Materials related:

(a) Properties of the fluid—viscosity.
(b) Nature of the solids—particle size, shape, size distribution and packing characteristics.
(c) Concentration of solids in suspension.
(d) Quantity of material to be handled.
(e) Whether it is necessary to wash the filtered solids
(f) Whether any form of pretreatment will be helpful

Equipment and process related:

(a) Flow rate.
(b) It should be absolute in the sense, the limit to size of particles passing through the filter should be known.
(c) It should be sterilisable by heat, radiation or gas (e.g. ethylene oxide and formaldehyde.)

(d) Independently checking the efficiency of filter. It should be economical.

Different forms of equipment are employed for filtration. Some of them are discussed below.

Critical Quality Attributes (CQAs) — Filtration

The CQAs along with process parameters (PPs) are recorded in Figure 10-7. The filtration is considered in the context of production of solutions. The upstream operation must be liquid-solid and/or liquid-liquid mixing and the downstream operation is bottling (filling) of the preparation. For a given set of conditions, the attributes critical in this step are: clarity (appearance), assay and microbial load. The clarity is evaluated by several ways as mentioned in Figure 10-7. The content uniformity does not become a problem, because the preparation is homogenous.

The process parameters optimized are: integrity test of the filter, the pressure difference and filtration period. These are controlled during the filtration and prefixed as standards with limits. Colour comparators are used. The above are general characteristics, but a few may change depending on the type of filter used.

Further filtration of sterile preparation is a special case of filtration and therefore the above attributes are applicable and a few special features

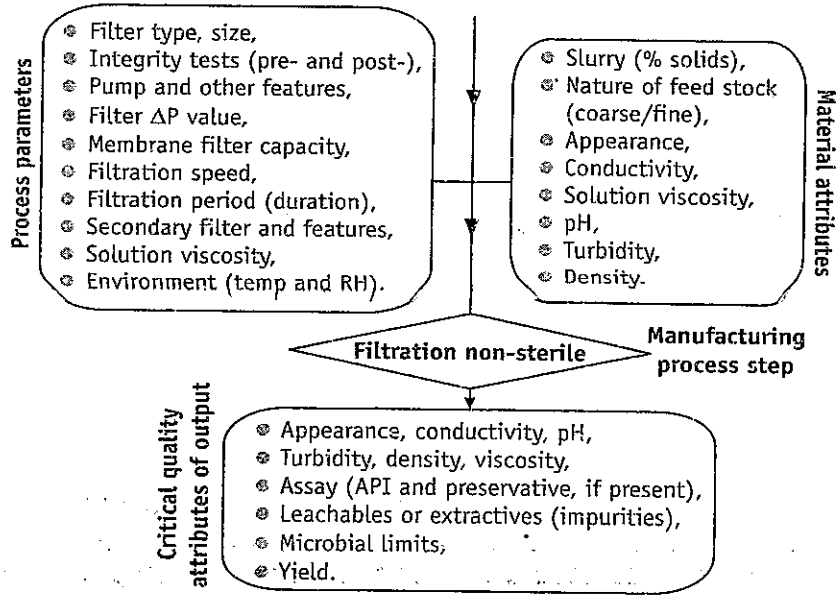


Figure 10-7. CQAs and process parameters for non-sterile filtration in the production of liquid preparations.

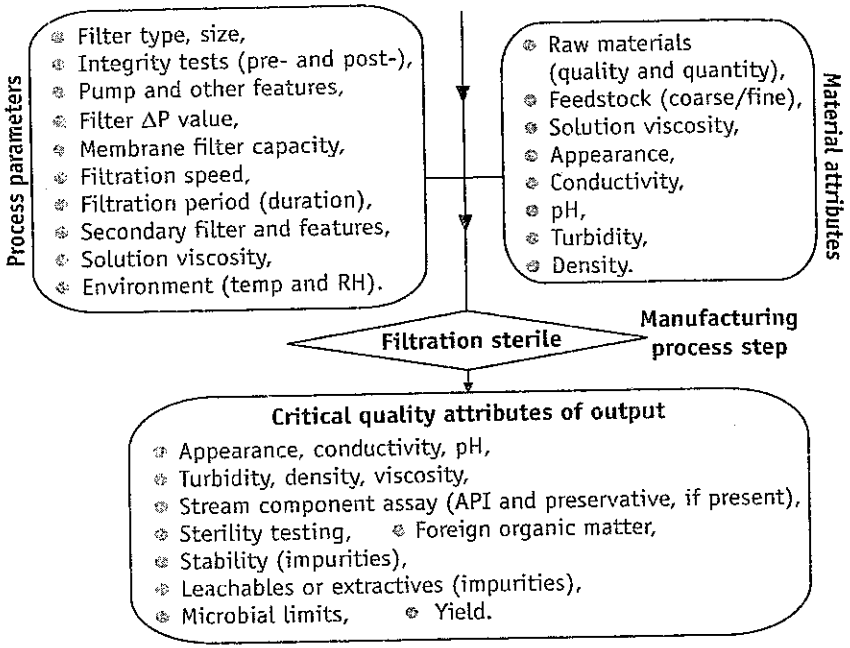


Figure 10-8. CQAs and process parameters for sterile filtration in the production of parenteral liquids.

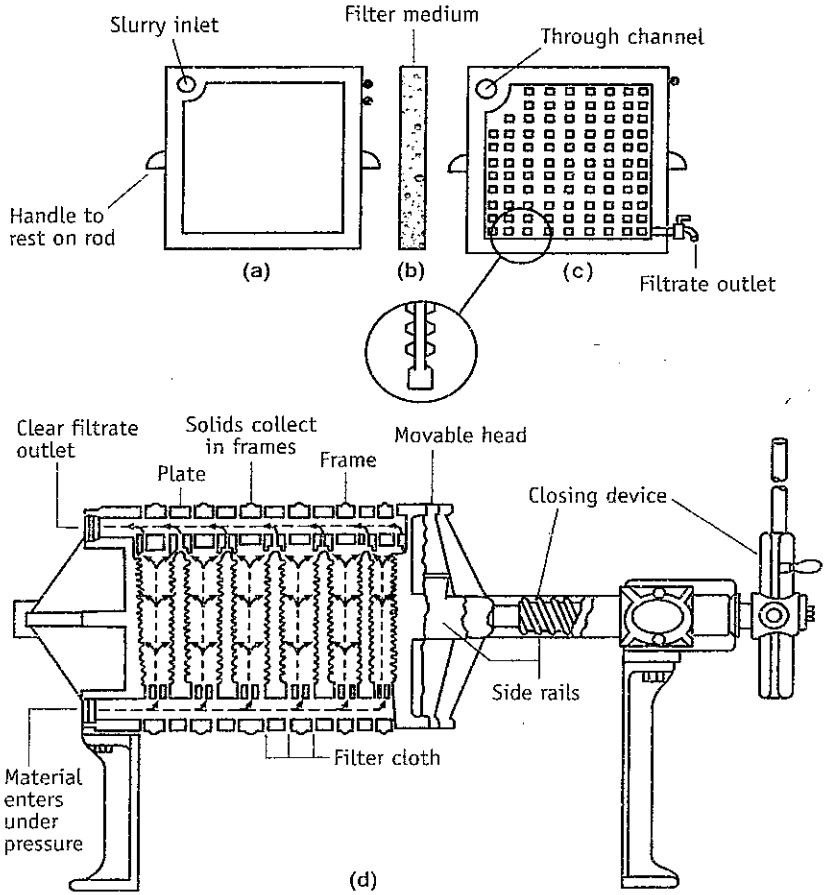
related to sterility are added (Figure 10-8). Sterile filtration can be considered as critical and directly affects the product quality. In addition to the filtration equipment, other accessories such as vent filter, sterile hold vessels, etc. must satisfy the sterility, because filtration alone is not equivalent to sterilization. A few critical attributes are foreign organic matter, sterility testing, etc. The above are general characteristics, but a few may change depending on the filtration equipment used.

Plate and Frame Filter Press

Principle : The mechanism is surface filtration. The slurry enters the frame by pressure and flows through the filter medium. The filtrate is collected on the plates and sent to the outlet. A number of frames and plates are used so that surface area increases and consequently large volumes of slurry can be processed simultaneously with or without washing.

Construction : The construction of a plate and frame filter press is shown in Figure 10-9. The filter press is made of two types of units, plates and frames. These are usually made of aluminium alloy. Sometimes, these are also lacquered for protection against corrosive chemicals and made suitable for steam sterilisation.

Frame contains an open space inside wherein the slurry reservoir is maintained for filtration and an inlet to receive the slurry. It is indicated by two dots in the description (Figure 10-9). The plate has a studded or grooved surface to support the filter cloth and an outlet. It is indicated by one dot in the description (Figure 10-9). The filter medium (usually cloth) is interposed between plate and frame.



(a) Frame—Maintains the slurry reservoir, inlet (eye) for slurry.
(b) Filter medium.
(c) Plate along with section—supports the filter medium, receiving the filtrate and outlet (eye).
(d) Assembly of plate and frame filter press.

Figure 10-9. Plate and frame filter press.

Frames of different thicknesses are available. It is selected based on the thickness of the cake formed during filtration. Optimum thickness of

the frame should be chosen. Plate, filter medium, frame, filter medium and plate are arranged in the sequence and clamped to a supporting structure. It is normally described by dots as 1.2.1.2.1 so on. A number of plates and frames are employed so that filtration area is as large as necessary. In other words, a number of filtration units are operated in parallel. Channels for the slurry inlet and filtrate outlet can be arranged by fitting eyes to the plates and frames, these join together to form a channel.

In some types, only one inlet channel is formed, while each plate is having individual outlets controlled by valves.

Working : The working of the frame and plate press can be described in two steps, namely filtration, operation and washing operation (if desirable).

Filtration operation : The working of a plate and frame press is shown in Figure 10-10. Slurry enters the frame (marked by 2 dots) from the feed channel and passes through the filter medium on to the surface of the plate (marked by 1 dot). The solids form a filter cake and remain in the frame. The thickness of the cake is half of the frame thickness, because on each side of the frame filtration occurs. Thus, two filter cakes are formed, which meet eventually in the centre of the frame. In general, there will be an optimum thickness of filter cake for any slurry, depending on the solid content in the slurry and the resistance of the filter cake.

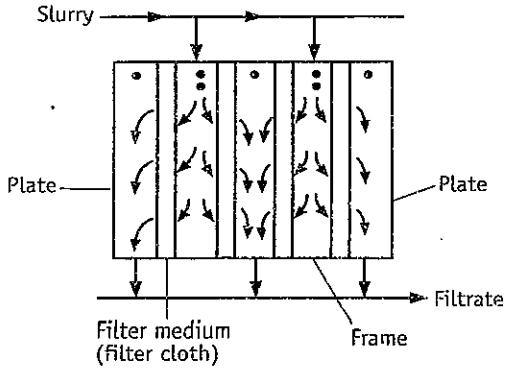


Figure 10-10. Plate and frame filter press, principle of operation (filtering).

The filtrate drains between the projections on the surface of the plate and escapes from the outlet. As filtration proceeds, the resistance of the cake increases and the filtration rate decreases. At a certain point, it is preferable to stop the process rather than continuing at very low flow rates. The press is emptied and the cycle is restarted.

Washing operation : If it is necessary to wash the filter cake, the ordinary plate and frame press is unsatisfactory. Two cakes are built up in the frame meeting eventually in the middle. This means that flow is brought

virtually to a stand still. Hence, water wash using the same channels of the filtrate is very inefficient, if not impossible. A modification of the plate and frame press is used. For this purpose, an additional channel is included (Figure 10-11). These wash plates are identified by three dots. In half the wash plate, there is a connection from the wash water channel to the surface of the plate.

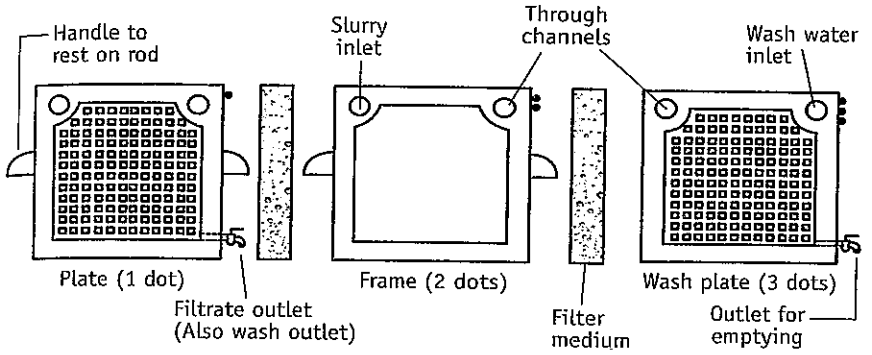


Figure 10-11. Plate and frame filter press with water wash facility.

The sequence of arrangement of plates and frames can be represented by dots as 1.2.3.2.1.2.3.2.1.2.3.2.1 so on (between 1 and 1, 2.3.2 must be arranged). Such an arrangement is shown in Figure 10-12(a) and (b) for the operations of filtration and water washing, respectively.

The procedure for washing the press is shown in Figure 10-12. The steps are as follows.

(1) Filtration proceeds in the ordinary way until the frames are filled with cake.

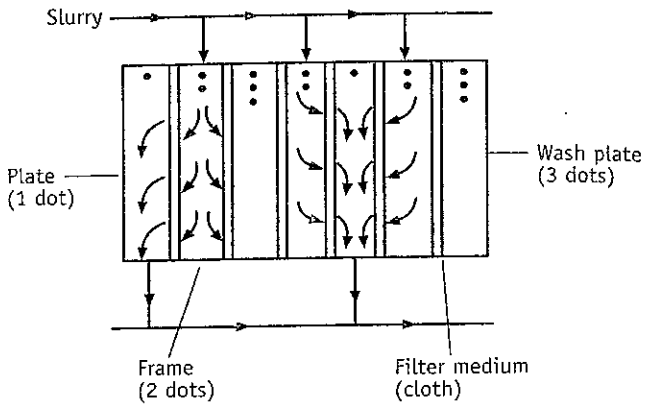
(2) To wash the filter cake, the outlets of the washing plates (three dots) are closed.

(3) Wash water is pumped into the washing channel. The water enters through the inlets on to the surface of the washing (three dots) plates.

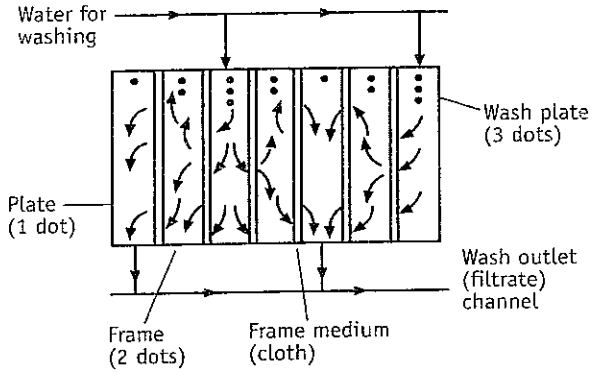
(4) Water passes through the filter cloth and enters frame (two dots) which contains the cake. Then water washes the cake, passes through the filter cloth and enters the plate (one dot) down the surface.

(5) Finally washed water escapes through the outlet of that plate.

Thus with the help of special washing plates, it is possible for the wash-water to flow over the entire surface of washing (three dots) plate, so that the flow resistance of the cake is equal to all points. Hence, the entire cake is washed with equal efficiency.



(a) Principles of filtration operation using the three types of plate and frame.



(b) Principles of cake washing using three types of plate and frame.

Figure 10-12. Plate and frame filter press. Principles of filtration and washing.

It should be noted that water-wash is efficient only if the frames are full with filter cake. If the solids do not fill the frame completely, the wash water causes the cake to break (on the washing plate side of the frame), then washing will be less effective. Hence, it is essential to allow the frames become completely filled with the cake. This helps not only in emptying the frames but also helps in washing the cake correctly.

Special provisions : (1) Any possible contamination can be observed by passing the filtrate through a glass tube or sight glass from the outlet on each plate. This permits the inspection of quality of the filtrate. The filtrate goes through the control valve to an outlet channel.

(2) The filtration process from each plate can be seen. In the event of a broken cloth, the faulty plate can be isolated and filtration can be continued with one plate less.

Uses : Filter sheets composed of asbestos and cellulose are capable of retaining bacteria, so that sterile filtrate can be obtained, provided that the whole filter press and filter medium have been previously sterilized. Usually steam is passed through the assembled unit for sterilization.

Examples include collection of precipitated antitoxin, removal of precipitated proteins from insulin liquors and removal of cell broth from the fermentation medium.

Heating/cooling coils are incorporated in the press so as to make it suitable for the filtration of viscous liquids.

Advantages:

(1) Construction of filter press is very simple and a variety of materials can be used.
- Cast iron for handling common substances.
- Bronze for smaller units.
- Stainless steel is used thereby contamination can be avoided.
- Hard rubber or plastics where metal must be avoided.
- Wood for lightness though it must be kept wet.

(2) It provides a large filtering area in a relatively small floor space. It is versatile, the capacity being variable according to the thickness of frames and the number used. Surface area can be increased by employing chambers up to 60.

(3) The sturdy construction permits the use of considerable pressure difference. About 2000 kilopascals can be normally used.

(4) Efficient washing of the cake is possible.

(5) Operation and maintenance is straight forward, because there are no moving parts, filter cloths are easily renewable. Since all joints are external, a plate can be disconnected if any leaks are visible. Thus contamination of the filtrate can be avoided.

(6) It produces dry cake in the form of slab.

Disadvantages:

(1) It is a batch filter, so there is a good deal of 'down-time', which is non-productive.

(2) The filter press is an expensive filter. The emptying time, the labour involved and the wear and tear of the cloth resulting in high costs.

(3) Operation is critical, as the frames should be full, otherwise washing is inefficient and the cake is difficult to remove.

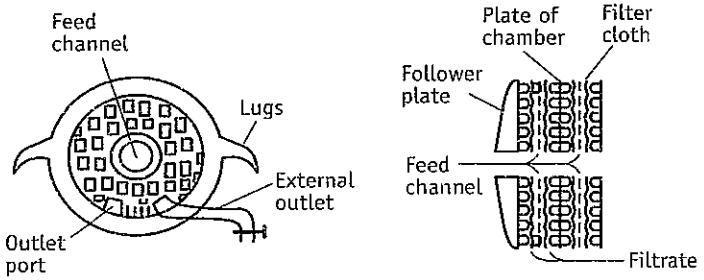
(4) The filter press is used for slurries containing less than 5 % solids. So high costs make it imperative that this filter press is used for

expensive materials. Examples include the collection of precipitated antitoxin and removal of precipitated proteins from insulin liquors.

Chamber Press

Principle : The mechanism is surface filtration. The slurry enters the frame by pressure and flows through the filter cloth. The filtrate is collected on the plates and sent to outlet. A number of head plates are used, so that the surface area can be increases and consequently large volumes of slurry can be processed simultaneously.

Construction : The construction of a chamber press is shown in Figure 10-13. It consists of a heavy fixed head plate made cast-iron. It is mounted on a suitable frame. Extending from the head plate, two horizontal bars support on both ends. The bars support the plates by lugs. At the centre of each press plate, a hole is provided for introducing the feed. The holes of all plates are connected on the head of press. Over each press plate, a sheet of filter cloth with a hole cut in the centre and is placed. The filter cloth is fastened by means of rings called 'grommets' and either screwed together or locked. These draw down the cloth, so that it is shaped round the plate. All such plates are arranged and a 'heavy follower plate' is placed behind and tightened. The cloth serves as a gasket between the adjacent plates.



(a) Cast iron plate of chamber press. (b) Principle of filtration.

Figure 10-13. Chamber filter.

Working : The feed (slurry) is pumped through the hole connected at the centre. The slurry passes through the cloth, runs down the corrugations on the face of the plates and escapes through the holes cored in the bottom of each plate. The filtrate passes through the outlet. The external outlet usually discharges into an open launder.

The space between the plates (formed by the raised edges) is the volume available for the formation cake. When sufficient cake is accumulated in the chamber, the closing screw is released. The plates are dismantled and the cake is discharged. Then, the plates are reassembled.

Uses : Chamber filter is used for clarification of syrups and filtrating of injection solutions.

Advantages : Chamber filter provides large filtering area in a relatively small floor space. A number of head plates can be increased or decreased as per the needs. Operation and maintenance are straight-forward, because there are no moving parts. Filter cloths is easily renewable.

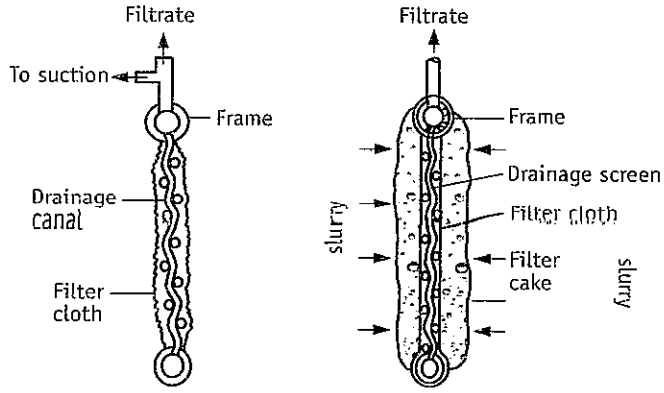
Disadvantages : Chamber press is not adaptable for washing the cake. The wear of the cloth is severe. The filtrate is usually not clear from the traces of fine particles.

Variants : In some equipment of chamber type, the feed may be introduced from a channel along the sides of the plates, instead of through the centre. The discharge connections may unite in a closed pipe.

Filter Leaf

Principle : Filter leaf is an apparatus consisting of a longitudinal drainage screen covered with a filter cloth. The mechanism is surface filtration and acts as sieve or strainer. Vacuum or pressure can be applied to increase the rate of filtration.

Construction : The general arrangement of a filter leaf is shown in Figure 10-14. It consists of a narrow frame enclosing a drainage screen or grooved plate. The frame may be of any shape, circular, square or rectangular. The whole unit is covered with filter cloth. The outlet for the filtrate connects to the interior of the frame through suction.



(a) Filter leaf (b) Filter leaf during filtration

Figure 10-14. Assembly of filter leaf.

Working : The filter leaf is immersed in the slurry. Vacuum system is connected to the filtrate outlet. The slurry passes through the filter cloth. Finally filtrate enters the drainage canal and goes through the outlet into

the receiver. Air is passed to flow in reverse direction which facilitates removal of cake.

Uses : The filter leaf is satisfactory, if the solid content of the slurry is not too high, about 5 %, i.e. dilute suspensions.

Advantages : (1) Filter leaf is a versatile piece of equipment. Filter leaf is probably the simplest form of filter used for batch processes.

(2) A number of units can be connected in parallel to increase the surface area for filtration.

(3) Pressure difference can be obtained either with vacuum or using pressure up to the order of 800 kilopascals.

(4) Labour costs for operating the filter leaf are fairly moderate.

(5) The efficiency of washing is high.

(6) Slurry can be filtered from any vessel. Simply immersing the filter in a vessel of water can wash the cake.

Variants : *Sweetland filter*—A variation is to enclose the filter leaf in a special vessel into which the slurry is pumped under pressure. In this form, a number of leaves are connected to a common outlet to provide a large area for filtration. A typical example of this kind is the Sweetland filter shown in Figure 10-15. The vessel is cylindrical and filter leaves are arranged so that they are supported by the upper part. The lower part can be swung away. This permits the cake to be discharged by compressed air while removing the filter leaves from the vessel.

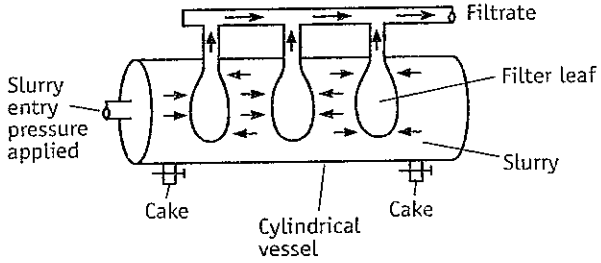


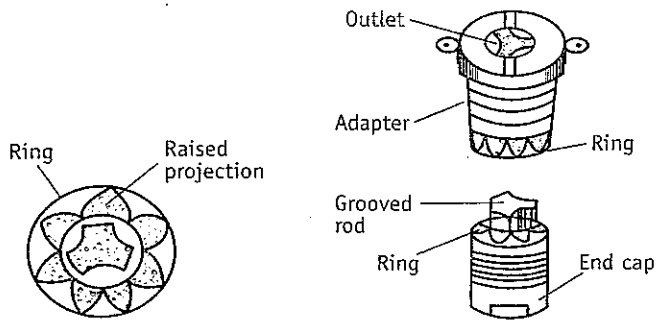
Figure 10-15. Sweetland filter.

Metafilter

Principle : Metafilter functions as a strainer (surface filtration) for the separation of particles. In this method, metal rings contain semicircular projections, which are arranged as a nest to form channels on the edges. This channel offers resistance (strainer) to the flow of solids (coarse particles). The clear liquid is collected into a receiver from the top.

Construction : The construction and assembly of a metafilter is shown in Figure 10-16. The metafilter consists of a series of metal rings. These

are threaded so that a channel is formed on the edges. It contains a grooved drainage column on which a series of metal rings are packed. These rings are usually made of stainless steel and have dimensions of about 15.0 mm internal diameter and 22.0 mm external diameter.



(a) Surface view of a ring. (b) Assembly of rings on column.

Figure 10-16. Metafilter.

Each metal ring has a number of semicircular projections (0.8 mm in thickness) on one side of the surface as shown in Figure 10-16a. The projections are arranged the same way up. These rings are tightened on the drainage column with a nut. Therefore, metafilter is also known as *edge filters*.

Working : The working principle of a metafilter is shown in Figure 10-17. These filters are placed in a vessel and may be operated by pumping the slurry under pressure or occasionally by the application of reduced pressure to the outlet side. The slurry passes through the channels formed on the edges between the rings. The clear liquid rises up and collected from the outlet into the receiver. Metafilter functions as a strainer (surface filtration).

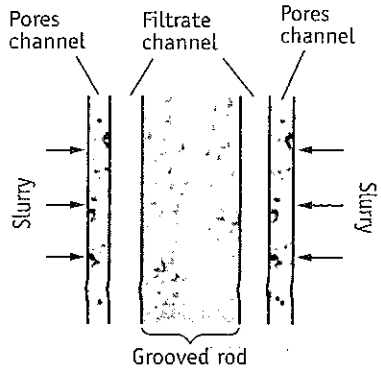


Figure 10-17. Mechanism of filtration through metafilter.

For the separation of fine particles, a bed of suitable material such as kieselguhr is first built up. The pack of rings serves essentially as a base on which the true filter medium is supported.

Uses : Metafilter can be used for:

- clarification of syrups
- filtration of injection solutions
- clarification of insulin liquors
- filtration of viscous liquids can be achieved by applying pressure

Advantages:

(1) Metafilter can be used under high pressures, without any danger of bursting the filter medium.

(2) Running costs are low, as separate filter medium is not used. The volume of residual hold up in the filter is less.

(3) It can be constructed from a material that can provide excellent resistance to corrosion and avoid contamination of sensitive products.

(4) It is an extremely versatile filter. It can be used for the filtration of very fine particles using filter aids. Large particles can be separated by building up of a bed of same particles.

(5) Removal of cake is carried out effectively, by simply back-flushing with water.

(6) Change over from one batch to another or one product to another is easy.

(7) Sterile products can be handled.

Cartridge Filter

Principle : Cartridge filter is a thin porous membrane in which pre-filter and membrane filter are combined into a single unit. The filtration action is mainly sieve-like and the particles are retained on the surface.

Construction : The construction of a cartridge filter is shown in Figure 10-18a. Cartridge filter has a cylindrical configuration made with disposable or changeable filter media. These are made of either plastic or metal. It consists two membrane filters (sieve-like) made of polypropylene: a prefilter and an actual filter for filtration. A protective layer surrounds them. The cartridges are housed in a holder. A number of cartridges can be placed in the same housing. The housing is closed with a lid. The housing has provisions for slurry inlet and filtrate outlet.

Working : The slurry is pumped into the cartridge holder. It passes through cartridge filter unit by the mechanism of straining. The clear liquid passes to the centre and moves up to collect through the outlet.

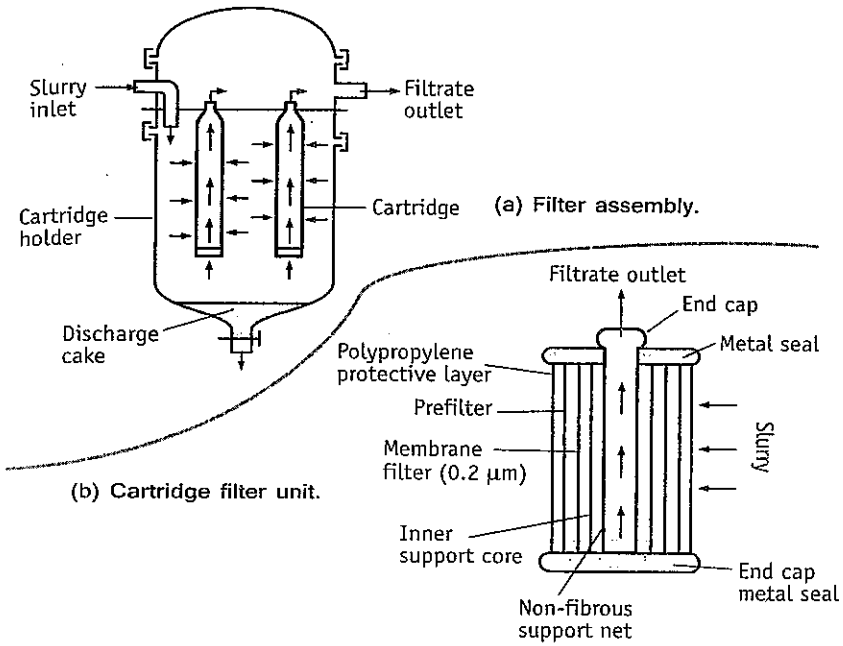


Figure 10-18. Cartridge filter.

Uses : Cartridge filter is particularly useful for the preparation of particulate free solutions for parenteral and ophthalmic uses. This filter holder will process 1000 to 15000 L of sterile solution per hour.

Advantages : (1) Stainless steel construction permits autoclaving for sterile operations.

(2) Cartridges with self-cleaning devices are advantageous.

(3) Rapid disassembling as well as reusing of filter media is possible.

(4) Cartridges are not brittle, when they are dry.

(5) They are used as in-line continuous filtration, which reduces handling of solutions. It minimizes the chances of contamination.

Disadvantages : (1) Cost of disposable elements offsets the labour saving in terms of assembly and cleaning of cartridge clarifier.

(2) A number of manufacturers provide the components, which are generally not interchangeable between suppliers.

Drum Filter

Principle : Rotary drum filter functions on the principle of filtering the slurry through sieve-like mechanism on a rotating drum surface, under the conditions of vacuum. In addition, compression, drying (using hot air) and removing the filter cake (using a knife) are possible.

Construction : The construction of a rotary drum filter is shown in Figure 10-19. It consists of a metal cylinder mounted horizontally. The drum may be up to 3 metres in diameter and 3.5 metres in length and gives a surface area of 33 metre square. The curved surface is a perforated plate, which supports a filter cloth. The drum is radially partitioned dividing the annular space into separate compartments. Each of it is connected by an internal pipe to the centre of the drum through a rotating valve.

Working : The drum is rotated at a speed less than one revolution per minute. The drum just enters the slurry in the trough (Figure 10-19). As it dips, vacuum is applied in this segment so that the solid is build up on the surface. The liquid passes through the filter cloth into an internal pipe and valve. Finally the filtrate reaches the collecting tank.

As the drum leaves the slurry section, it enters the drainage zone. Here excess of the liquid is drawn inside. Special cake compression rollers may be included at this stage, so that the cake is consolidated by the compression. This improves the efficiency of washing and drying process.

- Vacuum is applied to carry the slurry along with the drum
- Drainage zone
- Water washing arrangement
- Drying zone - dry air supply
- Cake removal zone

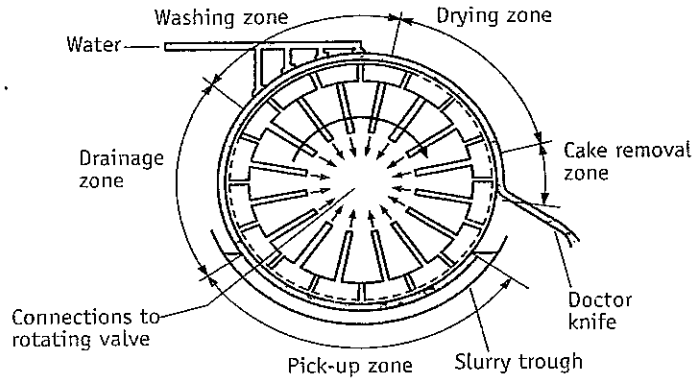


Figure 10-19. Drum filter.

As the drum leaves the drainage zone, it enters the water wash section. Water is sprayed on the cake. A separate system of vacuum is applied on the panel in order to suck the wash liquid and air through the cake of solids. Wash liquid is drawn through the filter into a separate collecting tank.

Then the cake enters the drying zone, where hot air is blown on the cake. The cake may have the moisture content less than one percent. Finally the cake is removed using a doctor knife and discharged.

All these steps are completed in one rotation of the drum. Now the drum is ready to receive a fresh lot of slurry.

Uses : Drum filter is used for continuous operation and is utilised to filter slurries containing high proportion of solids up to 15 to 30 %. In the production of penicillins, the extract is separated from mycelium (cell mass) by drum filters. These are used for collecting calcium carbonate, starch and magnesium carbonate.

Advantages : (1) Cake is removed simultaneously during operation. Therefore, suitable for use with concentrated slurries.

(2) The labour costs are very low on account of automatic and continuous operation of the rotary filter.

(3) The filter has large surface area.

(4) The speed of rotation can be varied and the cake thickness can be controlled. For example, if the solids form an impenetrable cake, the thickness may be limited to less than 5 mm. On the other hand, if the solids are coarse and form a porous cake, the thickness of 100 mm or more, can be obtained.

Disadvantages : (1) Rotary drum filter is expensive equipment with complex functioning. It contains moving parts and also requires a number of accessories such as vacuum pumps, vacuum receivers and traps.

(2) The cake tends to crack due to the air drawn through by the vacuum system. This makes washing and drying processes inefficient.

(3) The rotary filter is suitable only for straightforward slurries. It is less satisfactory, if the solids form an impermeable cake or it is difficult to remove the cake adequately.

Variants : *String discharge rotary filter* : It is especially used for filtering the fermentation liquor in the manufacture of antibiotics, where the mould is difficult to filter by ordinary methods, because it forms a felt-like cake. A number of loops of string are kept on the drum surface, which pass round the drum. The cake is formed on the strings. These strings lift filter cake off the filter medium and is thus removed.

Streamline Filter

Principle : Streamline filter consists of a column of filter elements held tightly together, so that the slurry (to be filtered) enters from the sides of the column and passes through very narrow channels between the elements. These filters employ paper discs. The filter acts as a strainer to retain solids.

Assembly : The assembly of a streamline filter is shown in Figure 10-20. It consists of specially treated filter paper discs arranged in the form of a

compressed pack on an upright rod or spigot (meaning peg for a hole in a cask). In assembling the filter, the two parts of the filter can be unscrewed. The required quantity of rings are placed on the spigot portion and the two parts are then screwed together to give a compact stack of the filter elements. The extent of compression on the disc may be varied depending on the size of the particles to be removed. For small scale filtration, ebonite material made spigots are used. The spigot is hollow and grooves run down the length. From hollow centre of the spigot, vacuum is applied.

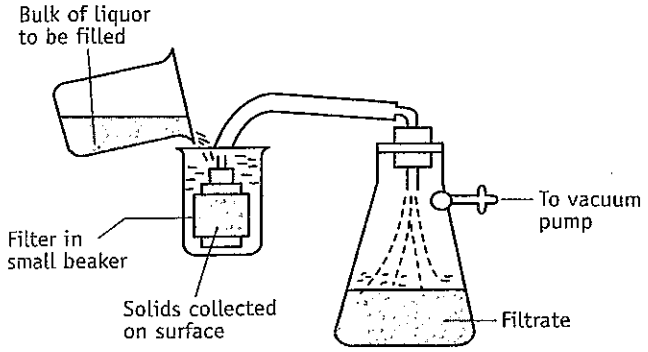


Figure 10-20. Small streamline filter assembly.

Working : The streamline filter is immersed in the liquid to be filtered. From the hollow centre of the spigot, vacuum is applied. The roughness of the paper surfaces offer narrow passage ways through which the clear liquid flows. Further, liquid also passes between the surfaces of the paper disks. The entire solid residue is left at the edge and the width of the pack. It is governed solely by the need for the mechanical strength in withstanding the pressure used in forcing the liquid through the pack. The clear liquid passes along the grooves, sucked through the hollow centre of the spigot and the filtrate passes to the receiver. After the last quantity of liquid is filtered, wash water may be used, if necessary.

Cleaning of the streamline filter is attempted by connecting the spigot to the water tap. Then water is passed in opposite direction. The residue is washed away from the edges of the stack. If solid residue is required, air may be blown, so that the solid is peeled off, which may be collected.

Uses : Streamline filter removes suspended matter, traces of fines and even submicron size colloidal matter from lager volumes of the slurry. The two parts of the spigots are screwed tightly and fine precipitates can be separated for achieving high grade polishing. Oily, aqueous and alcoholic solutions which do not soften the fibre of the pack can be also be filtered. Heat resistant porcelain filter is used for strongly acidic or hot strong alkaline liquids.

Advantages : Instead of vacuum, pressure may be applied. In this case, the container (in which the assembly is immersed) must be sealed and should be able to withstand the pressure applied. Spigots can be constructed using a variety of materials, namely ebonite, porcelain etc.

Pressure Sand Filter

Principle : The type is depth filtration and the mechanism is impingement and entanglement of solids on account of low pressure differential. The slurry enters the sand bed and the clear liquid is collected from the bottom outlet.

Construction : The construction of a standard pressure sand filter is given in Figure 10-21. It is a closed system and consists of a cylindrical tank with a bottom containing a number of brass strainers. These are mounted on a false bottom or connected to a manifold embedded in concrete. The strainers have narrow slots sawed in them. A layer of moderately coarse gravel is placed on the top. Above this, 6 to 12 m depth sand layer is placed, which acts as a filter medium. Baffles are arranged at the point of feed inlet, in order to prevent the disturbance of sand by direct stream. Provision is made at the bottom for collecting the filtrate.

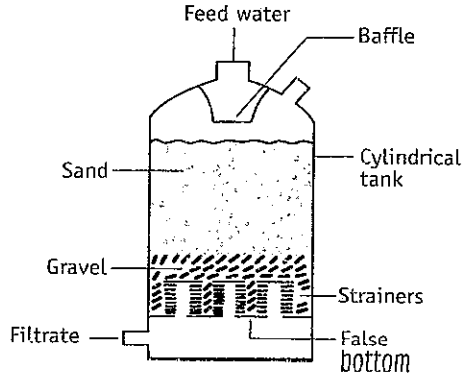


Figure 10-21. Pressure sand filter.

Working : The feed is introduced from the top at pressure through the baffle. The feed is passed smoothly at a uniform rate onto the sand medium. Filtration is achieved by straining mechanism through the sand medium. Then, the feed is passed through strainer, so that further filtration takes place and particles are retained. The precipitate is discarded. The filtrate is collected from the bottom.

When the precipitate clogs the sand (indicated by reduced filtration rate), back washing permits the regeneration of the filter bed. During this operation, water moves up through the sand bed and moves out from the inlet.

Uses : Pressure sand filter is used for filtration of boiler feed or water for similar purposes. Sand filters are mainly used when the solids are little and large volume of feed is to be handled. Such operations can be achieved at minimum cost. Pressure sand filters are applicable only to the separation of precipitates that can be removed from the sand.

Disadvantages : (1) Feed containing precipitates that are gelatinous or form a coat on the sand cannot be filtered through the sand filter, because back washing does not permit regeneration.

(2) If the feed contains finely divided solids, sand filter cannot be used for filtration.

(3) Sand filter cannot remove bacteria. In such cases, coagulants such as ferrous sulphate or aluminium sulphate, are added to the feed before filtration. The alkalinity of normal water permits the formation of flocs. These adsorb finely divided suspended matter and even bacteria. The flocs though fine are removed by the sand filter.

Variants : In open type sand filter, large concrete boxes are used. These filters use gravity filtration (hydrostatic head filter). This filter and accessories are extremely simple and the costs are low. The filtration rate is low and labour charges are high. This filter occupies more floor space.

Comment 10-7. What is meant by washing of the cake? When is it essential?
Comment 10-8. Is it possible to obtain the sterile liquid by filtration? Explain
Comment 10-9. Vacuum filtration is suitable for sterile preparations. True or false. Justify.

SELECTION OF FILTRATION EQUIPMENT

A number of product related factors should be considered, while selecting the filtration equipment. A few of these are mentioned below.

Properties of the Slurry

Viscosity of the slurry is an important factor. If the viscosity of the slurry is high, then elevated pressures or vacuum must be used. High operating pressure requires equipment with sufficient strength and appropriate safe operating procedures. Often it is necessary to heat the slurry. In such cases, steam heated jackets are to be fitted to the equipment. The equipment seals must be used to withstand the elevated temperatures.

The nature of solids, namely particle size, shape, size distribution, and packing arrangements should also be considered. These should be absolute in the sense, the limit to size the particles passing through the filter should be known. For the same purpose, filters are designated by number, namely pore size, etc.

Concentration of Solids in Suspension

A large load necessitates the use of pre-filter, where the cake can be continuously removed during filtration. If the solids are about 5 %, filter leaf can be used and scale of operation is small. If the solids are to be tune of 25 to 35 %, rotary drum filter or frame and filter press may be used.

Quantity of Material to be Handled

The volume of slurry to be filtered, filtration rate and the time needed for filtration dictate the size and type of equipment.

Degree of Filtration Required

Based on the degree of filtration required, the pore size of membrane or the filter grade is chosen. If sterility is required, then the equipment should itself be capable of being sterilised by heat, radiation and gas (examples are, ethylene oxide, formaldehyde, etc.). Similarly contamination must be prevented after the product is passed through the filter. Membrane filters are suitable for such purposes, if the scale of operation of small. For large scale operations, cartridge filter is preferred.

Interaction of Components of Filter and Slurry

The components of the filter may leach into the filtrate, degrade the components of the filtrate and adsorb the components of the filtered product. These factors influence the efficiency of the filtration process and quality of the filtered product.

Economic factors are equally important and need to be considered, while selecting the filtration equipment.

- Purchase, production and maintenance costs must be minimum.
- Washing the cake, dismantling, cleaning and assembling of the equipment must be easy.
- Corrosion of filter parts must be minimum.

The final choice of filtration equipment for a particular material depends on the detailed consideration of a variety of factors as mentioned above.

Comment 10-10. If the slurry contains 25 % solids or more, what is the type of filtration equipment employed? Why?

Summary

Filtration is a process of separation of solids from a fluid (slurry) by passing through a porous medium. If the slurry cotnains solids of low concentratin (<1.0 % w/v), the filtration is known as *clarification*. The solids are retained on the filter medium. The mecahnisms for filtration are: straining, impingement, entanglement and attractive forces. These are

broadly known as surface filtration (straining and impingement) and depth filtration (entanglement and attractive forces). Filtration is routinely used in the manufacture of sterile products, liquid orals, bulk drugs and also in waste water treatment.

In filtation operation, the liquid flows through the filter medium. The driving force for the flow is the pressure gradient. The rate of flow will be greater at the beginning of the filtration, since the resistance to flow through the filter medium is minimum. Once a filter cake is formed, its surface also acts as filter medium and the solids continuously add to the thickness of the cake. Poiseulle's equation considered the filtration as similar to the streamline flow of a lqiuid under pressure through capillaries (of filter medium). Darcy's equation assumed that the capillaries are highly irregular and nonuniform in size. Therefore, the radius is corrected and rate equation is approximated. The filtration is mimicked as permeability of liquid. Kozeny-Carman equation proposed the influence of compressibility of the cake on the flow rate. This is aplicable to depth filtration. Based on these theories, several factors are ideintified: surface area of the filter miedium, pressure-drop across the filter medium (applying pressure, reducing pressure and centrigual force) and visocisty of the slurry. These factors such as surface area and pressure differences are applied in the industrial practice. The magnitude of the resistance of the filter medium will change due to the layer of solids deposited earlier, which may block the pores or may form bridges over the entrance of the channels. In order to keep a low pressure-drop, avoid the plugging of pores, filter aids are added to the slurry.

Filtration equipment are classified based on the application of external forces: pressure filters, vacuum filters and centriugal filters. Based on the nature of filtration, equipment are also categoried as cake filter, clarifying filter and cross-flow filter. Bases on the operations, equipment are divided as batch type and continuous type. The selection of industrial equipment is based several considerations: material-related, equipment-related and process-related.

Plate and frame filter press is a frequently used filter, wherein the size of operation can be expanded by including more number of plates and frames. Washing facility is also provided. The entire filter press including the filter medium can be sterilized using steam. The press is used to collect precipitated antitoxin, removal of precipitated proteins from insulin liquor and removal of cell-broth from the fermentation medium. Chamber press works on the principle of surface filtration. Surface area can be increased by adding the number of plates in the chamber. Normally, it is used for clarification of syrups and filtering injection solutions. Filter leaf operates on the principle of surface filtration. It is useful for clarifying dilute suspensions (5 % w/v). More number of units can be connected in parallel. Metafilter works on surface filtration and used for clarification of syrups. Viscous liquids also can be filtered by applying pressure. Cartridge filter works on the principle of surface filtration and is used for clarification of parenteral and ophthalmic preparations. It is also used in on-line continous filtration. Rotary drum filter functions on surface filtration and is used for continuous process, in the production of penicillin, wherein the mycelium is separated. Streamline filter works on surface filtration and used for clarifying the dispersions. Pressure sand filter is a depth filter and used when the solids are little and large volume of feed is to be handed. Keeping in view of the diverse applications, it is necesary to understand the construction and working of the industrial equipment. It is also important to select the filtration equipment to suit the specific needs of a product.

Glossary of Symbols

A = Surface area of the porous bed (filter medium), m^2.
ε = Porosity of the cake.
η = Viscosity of the filtrate, Pa·s.
K = Constant in Kozeny-Carman equation.
K = Permeability coefficient in Darcy's equation, m^2.
L = Thickness of the cake (capillary length), m.
ΔP = Pressure difference across the filter, Pa.
r = Radius of the capillary, m.
S = Specific area of the particles comprising the cake in Kozeny-Carman equation, m^2/m^3.
V = Rate of filtration, i.e. volume of liquid flowing in unit time, m^3/s.

QUESTION BANK

Each question carries one mark

Note : Encircle the alphabet which corresponds to the single best response.

1. Filtration is a unit operation that is commonly used for collecting:
   A. filtrate B. particulate matter
   C. precipitate D. slurry
2. In clarification process, which is the factor more important?
   A. Depth of the media B. Pore size of the filter media
   C. Surface area of filter D. Volume of slurry
3. Who has proposed that the filtration process is similar to the streamline flow of a liquid under pressure through capillaries?
   A. Carman B. Darcy
   C. Kozeny D. Poiseuilli

4. The fluid flows through the filter medium by virtue of:
   A. potential difference across the filter
   B. pressure difference across the filter
   C. temperature difference across the filter
   D. volume difference across the filter
5. Filter aids are mainly used when:
   A. liquid is required as product
   B. filter medium is not available
   C. solid and liquid are required as products
   D. solid is required as product
6. On what aspect of pressure does the filter leaf work?
   A. Atmospheric pressure B. Negative pressure
   C. Normal pressure D. Pressure is zero
7. Which one of the following is NOT a mechanism of filtration?
   A. Entanglement B. Impact
   C. Impingement D. Straining
8. Cellulose membrane filter is an example for which type of filtration?
   A. Cake filtration B. Decantation filtration
   C. Depth filtration D. Screen filtration
9. Which of the following acts as a mechanical support for the filter cake and is also responsible for the collection of solids?
   A. Feed B. Filter aid
   C. Filter medium D. Funnel
10. The efficiency of filtration increases if:
   A. compressibility of solids is high
   B. filter aid is added to the slurry
   C. filter medium is used
   D. size distribution of solids is wide in slurry
11. Which is the operation that is next to filtration?
   A. Centrifugation of filtrate B. Distillation of filtrate
   C. Drying of solids D. Washing of filter cake
12. One of the following equations is used for explaining the theory of filtration?
   A. Darcy's equation B. Stefan-Boltzmann equation
   C. Stokes equation D. Dalton's equation
13. For sterile filtration, one the following techniques is used.
   A. Cake filtration B. Depth filtration
   C. Electrostatic filtration D. Surface filtration

14. Which one of the following is NOT an example for filter aid?
   A. Activated charcoal B. Bentonite
   C. Kaolin D. Talc
15. Which one of the following is NOT a characteristic of filter aid?
   A. Chemically active B. Porous
   C. Recoverable D. Removes coloured substance
16. Which one of the following mechanisms is involved in case of meta filter?
   A. Cake filtration B. Depth filtration
   C. Surface filtration D. Zig zag filtration
17. In the filter press operation, the plates, frames and washing plates are arranged in the following sequence (1 represents plate, 2 represents frame and 3 represents washing plate).
   A. 1.2.3.1.1.2.3.1 B. 1.2.3.2.2.3.2
   C. 1.2.3.2.1.2.3.2.1 D. 1.2.3.1.2.1.3.1
18. Which is the filter used for clarification of syrups?
   A. Drum filter B. Filter leaf
   C. Meta filter D. Plate and frame
19. Which one of the following types of filters is suitable for separation of mycelium from a penicillin broth?
   A. Cartridge filter B. Leaf filter
   C. Membrane filter D. Rotary drum filter
20. Which is the filter made of polypropylene?
   A. Cartridge filter B. Meta filter
   C. Rotary drum filter D. Plate and frame filter
21. The pores in the stainless steel plates act as channels in one of the following filters?
   A. Cartridge filter B. Drum filter
   C. Leaf filter D. Meta filter
22. Which is the filter known as edge filter?
   A. Cartridge filter B. Filter leaf
   C. Filter press D. Meta filter
23. Apart from filtration, candle filter is used in which of the following processes?
   A. Decolouration of liquid B. Disinfection process
   C. Fermentation process D. Sterilisation of liquid
24. Which one of the following filters is used for a batch type?
   A. Drum filter B. Filter leaf
   C. Filter press D. Sweetland filter

25. In the plate and frame filter press, which is the mechanism involved in the filtration?
    A. Cake filtration B. Depth filtration
    C. Electrostatic filtration D. Surface filtration
26. Filtration is also known as clarification, when slurry contains not exceeding certain percent w/v solids.
    A. 0.01 B. 0.1
    C. 1.0 D. 10.0
27. Which of the following mechanisms is involved in 'depth filtration'?
    A. Electrostatic filtration B. Entanglement
    C. Impingement D. Straining
28. In filter press, heating/cooling coils are incorporated in the press, which are suitable for filtration of one of the following formulations?
    A. Antibiotic solution B. Injection solution
    C. Ophthalmic solution D. Syrups
29. Sweetland filter is a variant of:
    A. cartridge filter B. drum filter
    C. filter leaf D. meta filter
30. Which one of the filters consists of pre-filter and final filter?
    A. Cartridge filter B. Meta filter
    C. Rotary drug filter D. Sweetland filter
31. Which one of the following filters represents a pressure filter?
    A. Centrifugal filter B. Frame and plate filter
    C. Metafilter D. Rotary drum filter
32. The porous medium used to retain the solids is known as:
    A. filter aid B. filter cake
    C. filter medium D. slurry

Each question carries 2 marks

1. List the factors influencing the rate of filtration.
2. Write Kozeny-Carman equation and give its significance.
3. List the functions of filter aids.
4. Give the principle of filtration process.
5. Differentiate between pressure filtration and vacuum filtration.
6. List the properties of filter aids.
7. Distinguish filtration and clarification.
8. What are filter aids? Give two examples.
9. Differentiate surface filtration and depth filtration.
10. What is meant by the word 'sinter'? List the uses and advantages of sintered glass filter.

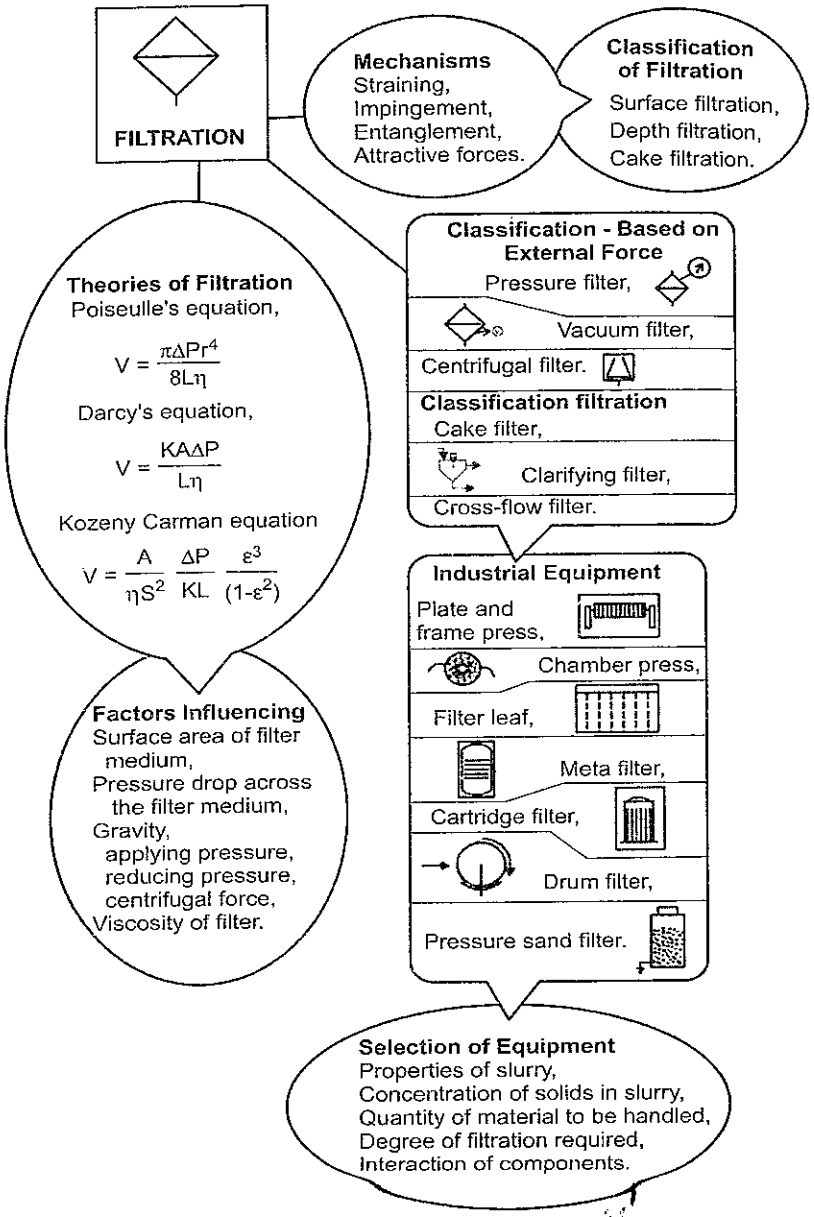
11. What is the mechanism of filtration in membrane filter? What are its advantages and disadvantages of membrane filters?
12. Give a neat labelled diagram of pressure sand filter. What are its uses?
13. Why depth filtration is necessary for the separation, while other methods are available?
14. Explain the mechanism by which filter aids improve the rate of filtration.
15. What is the difference between depth filtration and cake filtration?
16. What are the conditions in which pressure sand filter is used? Why?
17. Explain the method of washing the residue with a suitable example of filtration equipment.
18. What is meant by 'back washing'? How is it achieved in filtration?
19. Suggest a method of filtration using vacuum. Explain its role in the filtration.

Each question carries 5 marks

1. Explain the mechanisms of filtration.
2. What are filter aids? Name the filter aids commonly used in pharmacy practice.
3. Describe the construction and working of a rotary continuous filter.
4. Describe the construction and working of leaf filters.
5. Describe the construction and working of a preferred filter suitable for filtration of viscous liquids.
6. Describe the assembly and working of streamline filter with a neat diagram.
7. Explain any five factors affecting the selection of filtration equipment.

Each question carries 10 marks

1. Explain the construction, working, advantages and disadvantages of filter press.
2. Explain the theories of filtration giving the principle, mechanism and factors affecting the process.
3. With a neat diagram, describe the construction and working of a suitable industrial filter for handling of high solid containing slurries.
4. With a neat diagram, describe the construction and working of an industrial filter suitable for clarification of syrups.
5. With a neat labelled diagram, describe the construction and working of a chamber press.



MINDMAP OF FILTRATION OPERATION – KNOWLEDGE BASE

CHAPTER 11

Centrifugation

Theory of Centrifugation
Classification of Centrifuges
Laboratory Centrifuges
Industrial Equipment

LEARNING OBJECTIVES

After reading this chapter, the reader should be able to:

- Understand the process of centrifugation as a separation operation with distinct applications.
- Explain the theory of centrifugation for identifying the factors for production.
- Highlight the classification of centrifuges based on the principles of separation and scale of operation.
- Explain the principle, construction, working and uses of equipment of industrial scale.

Centrifugation is a unit operation employed for separating the constituents present in a dispersion with the aid of centrifugal force.

Centrifugal force provides the driving force for the separation. It replaces gravitation forces operating during the sedimentation. Centrifugation is particularly useful when separation by ordinary filtration is difficult, for example, separating highly viscous mixtures and colloidal dispersions (particle size < 5 μm), in which difference in the densities is less. Centrifugal separation is faster compared to filtration (gravity). The degree of separation if high, because the forces applied are of high order of magnitude. In short, centrifugation provides a convenient analytical method of separating either two immiscible liquids or a solid from a liquid (biochemical or microbiological). The equipment used for the separation are known as *centrifuges*.

Process of Centrifugation

The centrifuge consists of essentially a container in which a mixture of solid and liquid or two liquids is placed and rotated at high speeds. The

mixture is separated into its constituent parts by the action of centrifugal force on their densities. A solid or liquid of higher specific gravity is thrown outward with greater force. Therefore, it is retained at the bottom of the container leaving a clear supernatant layer of pure liquid.

The speed of a centrifuge is commonly expressed in terms of the number of rotations per minute of the rotor.

Applications

Production of bulk drugs : Centrifugation technique is used to separate crystalline drugs such as aspirin from the mother liquor. Free flowing product results due to the removal of traces of mother liquor and avoidance of effervescence.

Production of biological products : Most of the proteinaceous drugs and macromolecules are present as colloidal dispersion in water. By normal separation methods, it is difficult to produce them in large scale. Centrifugal methods are used for the separation of these constituents from water. Insulin can be obtained in pure form by selectively precipitating other fractions of proteins and subsequently separating them by ultracentrifugation. Centrifugation is employed for separating the blood cells from blood.

Biopharmaceutical analysis of drugs : Drugs present in the blood, tissue fluids and urine are normally present in the form of colloidal dispersions. Centrifugation is used for separating the drugs. This method is essential for the evaluation of pharmacokinetic parameters and bioequivalence studies.

Evaluation of suspensions and emulsions : Centrifugation method is used as a rapid empirical test parameter for the evaluation of suspensions and emulsions. Normally, creaming is slow process in emulsions. This process can be hastened by inducing stress condition (using a centrifuge). A stable emulsion should not show any signs of separation even after centrifuging at 2000-3000 rotations per minute at room temperature.

Determination of molecular weight of colloids : Determination of molecular weight of a polymer is not possible by usual methods. Ultracentrifugation methods are used for determination of molecular weight of serum albumin, insulin and methylcellulose. Centrifugation (ultra-centrifugation) is also used for ascertaining the degree of homogeneity of the sample. For example, insulin is a monodisperse protein composed of two polypeptide chains, whereas gelatin is found to be polydisperse protein with fractions of molecular weight 10,000 to 1,00,000.

This chapter deals with the principles of centrifugation, equipment used and examples of the use of the methods in pharmacy practice on commercial scale.

Comment 11-1. What is the relationship between sedimentation force and centrifugal force?

Comment 11-2. Physical stability of the emulsion can be evaluated with the aid of centrifugation. True or false. Justify.

Comment 11-3. What is the use of centrifuge in bioequivalence studies?

THEORY OF CENTRIFUGATION

In a colloidal dispersion, the dispersed phase may be either a solid or a liquid. Particles having a size above 5 μm sediment at the bottom due to gravitation force. In such cases, separation of solids is possible by simple filtration. If particles are of the order of 5 μm or less, they undergo Brownian motion. Hence, they do not sediment under gravity. Therefore, a stronger force, centrifugal force is applied in order to separate them. The sedimentation also depends on the densities of the dispersed phase and dispersion medium. If the difference in the densities of these phases is less, again separation is difficult. By applying centrifugal force, it is possible to facilitate (increase the rate of sedimentation) the separation process.

Centrifugal Effect or Relative Centrifugal Force (RCF)

The centrifugal operation is described by equations including the gravitational constant. The derivation is as follows.

Consider a body of mass m kg rotating in a circular path of radius r metres at a velocity of v metre per minute (Figure 11-1). The force acting on the body in a radial direction is given by:

Force acting in radial direction,

$$F = \frac{mv^2}{r} \qquad ...(1)$$

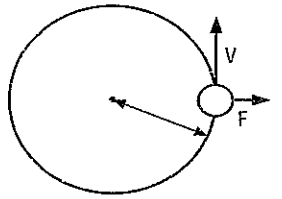


Figure 11-1. Principle of centrifugation.

where F = centrifugal force, N

The same body is experiencing gravitational force (newton). It can be expressed as:

$$\text{Gravitation force, } G = mg \qquad ...(2)$$

where g = acceleration due to gravity, m/s^2

The *centrifugal effect* is expressed as a ratio of centrifugal force to gravitational force. In other words, centrifugal effect is a force, which is a number of times greater than the gravitation force.

Separating power of a centrifuge is expressed as a ratio of the centrifugal force to the gravitation acceleration. This ratio may have a value as high as 10^4.

The centrifugal effect can be expressed as:

$$\text{Centrifugal effect, } C = \frac{\text{force acting in radial direction}}{\text{gravitational force}} = \frac{F}{G}$$

But $v = 2\pi rn$, where n = speed of rotation (revolutions per second of centrifuge). Substituting this in equation (3) yields

$$C = \frac{(2\pi rn)^2}{gr} = \frac{4\pi^2 r^2 n^2}{gr} = \frac{4\pi^2 r n^2}{g} \quad ...(4)$$

Since $2r = d$, where d = diameter of the rotation. Substituting the value in equation (4) gives:

$$C = \frac{2\pi^2 d n^2}{g} \quad ...(5)$$

The gravitational constant has a value of 9.807 m/s^2, so that equation (5) can be simplified as:

$$\text{Centrifugal effect} = 2.013\, n^2 d \quad ...(6)$$

In equation (6), n is expressed in s^{-1} and d is in metres

The measurement of d is made from the free surface of liquid (or from the tip of the tube) to the centre of a centrifuge and should be mentioned while reporting the centrifugal effect.

From equations (5) and (6), it can be inferred that

- Centrifugal effect $\propto$ diameter.
- Centrifugal effect $\propto$ (speed of rotation)^2.

Equation (5) helps in the selection of the type of centrifuge and other experimental conditions.

- If it is required to increase the centrifugal effect, it is of greater advantage to use a centrifuge of the same size (tubular with a length to diameter ratio varies from 4 to 8) at a higher speed rather than using a larger centrifuge at the same speed of rotation.
- It is always better to use the smallest size of centrifuge that has the appropriate capacity, since the centrifuge (equipment) is subjected to considerable stress in operation, largely due to the pressure of the fluid on the walls. It can be shown that the pressure is directly proportional to the square of the speed and the diameter. This principle is useful for the separation of two liquids as in emulsions.
- The centrifuge is designed to suit the required purpose. If a large amount of material is to be processed and a low centrifugal effect is sufficient to separate, then it is economical to use a large centrifuge operating at a low speed.

- The centrifugal sedimentation of very small particles requires high centrifugal effect. For this purpose, equipment of a small diameter is used, but operated at very high speed, e.g. tubular bowl centrifuge.

The centrifuge is comparable to a pressure vessel. Therefore, it must be handled with the same care as that of a high-pressure autoclave.

Comment 11-4. Suggest a centrifuge which can give high centrifugal effect.

CLASSIFICATION OF CENTRIFUGES

Centrifuges are classified based on their mechanisms of separation.

Sedimentation Centrifuge

Sedimentation centrifuge is a centrifuge that produces sedimentation of solids based on the difference in the densities of two or more phases of the mixture.

The efficiency depends on the velocity of rotation to which the mixture is subjected. E.g. horizontal continuous centrifuge, supercentrifuge and conical disc centrifuge.

Ultracentrifugation : When extremely fine solid matter is to be separated from a liquid for example in colloidal research, ultracentrifuge is used. In this instrument, a relatively small rotor is operated at speeds exceeding 1,00,000 rotations per minute and with forces up to one million times gravity.

Centrifuges have replaced the gravity separators to a considerable extent in production operations because of their effectiveness in separation.

Uses:

(1) Suspensions containing low concentration of solids can be separated quickly.

(2) Lanolin is recovered from the wool by scouring process.

(3) Olive and fish liver oils are purified by removing dirt and water.

(4) The liquid/liquid phases are separated in the extraction of drugs, for example, manufacture of antibiotics.

(5) Bacterial enzymes are prepared by removing bacteria.

(6) Blood plasma is separated from whole blood.

(7) Starch is collected after washing and purification stages.

(8) In the manufacture of insulin, liquor is clarified so as to remove the precipitated proteins.

Advantages:

(1) Centrifuges are compact and occupy a very small space.

(2) The separating efficiency is very high, so that the particles are deposited very rapidly. It is suitable, if the sediment is a fluid deposit or sludge.

(3) Two immiscible liquids are easily separated on a continuous process.

(4) By controlling the speed of rotation and rate of flow, coarse particles are separated, while finer particles remain in the suspension.

Disadvantages:

(1) The construction of sedimentation centrifuges is complicated.

(2) Its capacity is limited.

Filtration Centrifuge

Filtration centrifuge is a centrifuge in which solids pass are retained by porous medium allowing liquid to rush out due to centrifugal effect.

In this type the container contains a porous wall through which the liquid phase may pass and on which the solid phase is retained. E.g. are perforated basket centrifuge and semi-continuous centrifuge. The solids that form a porous cake can be separated in the filtration centrifuge. Normally perforated wall such as canvas or metal cloth is covered with a filter medium.

Uses:

(1) When solid recovery is the primary goal, centrifugation must be considered as an alternative to simple filtration.

(2) It is also used for removing unwanted solids from a liquid. For example, precipitated proteins are removed from insulin.

Advantages:

(1) It can handle slurries with a high proportion of solids and even those having paste like consistency.

(2) The final product has very low moisture content.

(3) The dissolved solids are separated from the cake.

Disadvantages:

(1) The entire cycle is complicated resulting in considerable labour costs.

(2) It is a batch process or semi-continuous type.

(3) The solids may form a hard cake, due to the centrifugal force, which is difficult to remove.

Classification Based on Scale of Usage

Laboratory scale : Horizontal spinning arm type
Angle centrifuge (45 to 50 angle)
High speed centrifuge (10,000 rotations per minute)
Ultracentrifuge (85,000 rotations per minute)

Commercial scale

Batch type : Perforated basket centrifuge
Semi-continuous scale : Short-cycle batch centrifuge
Continuous centrifuge : Supercentrifuge

Comment 11-5. How is sedimentation centrifugation different from filtration centrifugation?

Comment 11-6. Filtration centrifuge is a modification of filtration equipment. True or false. Justify.

Comment 11-7. What is the major limitation of a filtration centrifuge over filter?

LABORATORY CENTRIFUGES

Centrifuges separate two substances of different densities by the application of centrifugal forces which may be several times that of the gravity. Centrifuges used for the laboratory work are described in the following sections.

Horizontal Arm Type Centrifuge

The construction of a simple manually driven laboratory centrifuge is shown in Figure 11-2. It consists of a rotating head carrying two or four freely swinging metal buckets. Glass centrifuge tubes are filled with the material to be separated and placed into the metal buckets. The head is driven manually using crank. When head starts rotating, the metal buckets start swinging outwards and finally reach the horizontal position at maximum working speed. During this process, the particles (which are normally denser than the liquid) sediment along the side (length) of the tube and

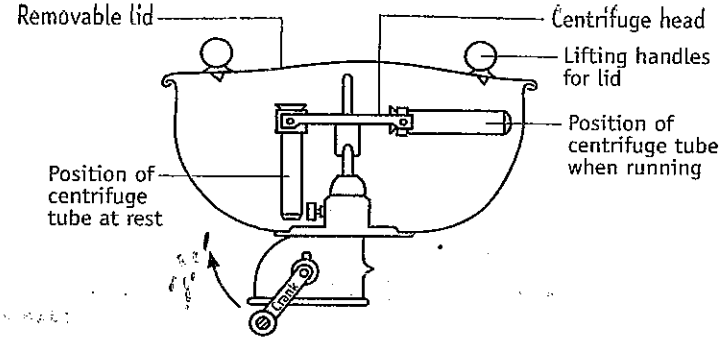


Figure 11-2. Horizontal arm centrifuge- Manually driven.

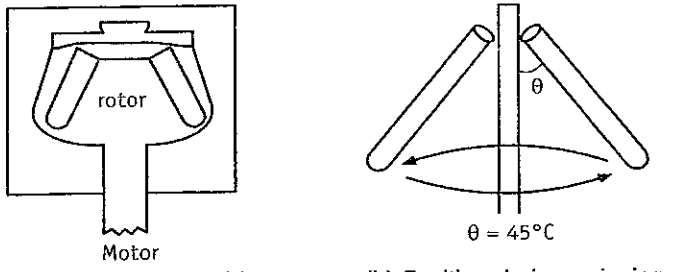
finally reaches the bottom of the tube. The contents of centrifuge tubes (either suspension or emulsion) undergo separation based on their densities. Once the crank is stopped, rotating head along with buckets reach the resting position. Then, centrifuge tubes are removed and decanted to collect supernatant liquid (low density phase). The sediment mass (high density phase) can then be collected.

This centrifuge is used for small volumes. This is also known as low speed centrifuge. The RCF obtained in small centrifuges is at 2000 g, at approximately 5000 rotations per minute.

Angle Centrifuge

The construction of a angle centrifuge is shown in Figure 11-3. It consists of electrically driven head carrying metal buckets. The unique feature of this centrifuge is that metal buckets (carrying centrifuge tubes) are held at 45 to 50° to the vertical axes, at resting as well as rotating position. This centrifuge is operated at high speed so as to get RCF of 10,000 g.

During centrifugation, the high density particles have only a short path to travel to reach the sides of the tube. The particles present in the liquid should sediment rapidly and should not adhere to the sides of the tube.



(a) Centrifuge motor drive. (b) Position during swinging.

Figure 11-3. Electrically driven angle centrifuge.

INDUSTRIAL EQUIPMENT

Centrifuges of different types are available to meet the specific requirements of the slurry and the end product. In addition, experimental conditions are established by considering the factors affecting the process.

- Nature of slurry
- Flow of feed or slurry
- Centrifuge dimensions
- Densities of the materials to be separated
- Bottle (centrifuge) size
- Centrifugation time

Critical Quality Attributes (CQAs) – Centrifugation

The CQAs, process parameters (PPs) and material attributes are recorded in Figure 11-4. The centrifugation is a separation process (alternative to filtration), but it is rarely used in the formulation development of solutions. Centrifugation is considered in the context of production of bulk drugs, process chemistry and biopharmaceutical products. In all these cases, the solid is important output. The upstream operation must be extraction of liquid-liquid or solid-liquid type and downstream operation is drying of solids. For a given set of conditions, the attributes critical to the steps are: assay, moisture content and flow properties.

The process parameters are: density differences, g-number, rpm and duration of centrifugation. These are prefixed as standards with limits and attempted to control in the production. The above are general characteristics, but a few may change depending on the type of centrifuge used (filtration type or sedimentation type).

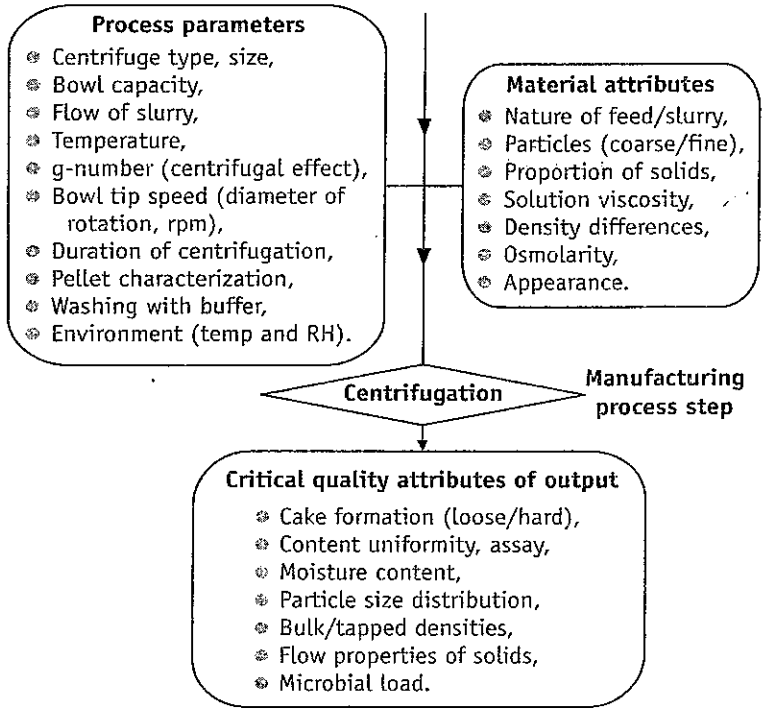


Figure 11-4. CQAs and process parameters for centrifugal separation in the production of bulk drugs.

Some pharmaceutically important centrifuges are explained below.

Perforated Basket Centrifuge

In this centrifuge, a basket is mounted above a driving shaft. Such an arrangement is described as *under-driven*. Conversely, if the basket is

suspended from a shaft, it is described as over-driven. These are used for batch processes. An under-driven bowl centrifuge is described below.

Principle : Perforated basket (bowl) centrifuge is a filtration centrifuge. The separation is through a perforated wall based on the difference in the densities of solid and liquid phases. The bowl contains a perforated side-wall. During centrifugation, the liquid phase passes through the perforated wall, while solid phase is retained in the bowl. The solid is removed after cutting the sediment by a blade when the centrifuge stops.

Construction : The construction of a under-driven perforated basket centrifuse is shown in Figure 11-5. It consists of a basket, made of steel (sometimes covered with vulcanite or lead) or copper or monel or any other suitable metal. The basket material of construction should be such that it offers the greatest resistance to corrosion. The basket may have a diameter of 0.90 m and a capacity of 0.085 m^3. The diameter of the perforations should be selected based on the size of crystals to be separated. In case, the size of perforations is bigger than that of the particles, a filter cloth is employed.

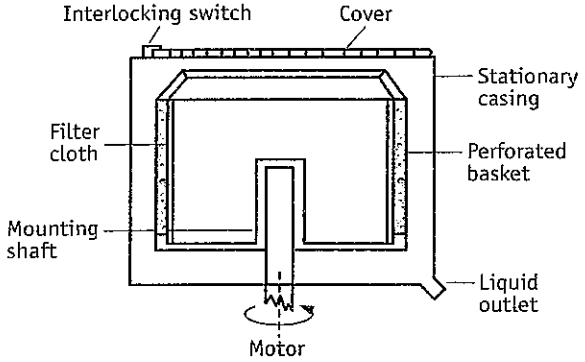


Figure 11-5. Construction of perforated basket centrifuge.

The basket is suspended on vertical shaft and is driven by a motor using suitable power systems such as belt pulleys, water turbines and electric motors. The basket may require about 5 kilowatt power for starting and 2 kilowatt power for running. Sometimes, steel hoops are used externally to strengthen the basket. Surrounding the basket, a casing (stationary) is provided which collects the filtrate and discharges it at the outlet.

Working : The material (feed) is kept in the basket when the basket is stationary. The amount of material should be optimum, otherwise, during centrifugation it puts a great strain on the basket. The loading of material must be done to give even distribution. Power is applied to rotate the basket and maximum speed must be attained quickly. The basket runs at 1000

rotations per minute. The power required for running is small compared to the power required for starting and bringing it to the full speed.

During centrifugation, the liquid passes through the perforated wall, while the solid phase retains in the basket. The liquid leaves the basket and is collected at the outlet. The cake is then spun to dry as much as possible. Sometimes higher speeds are used so that the cake will be completely dried. After a definite period of time, the power is turned off. By applying a brake the centrifuge is stopped. The basket is brought to rest. The solid cake is cut using a blade and then unloaded manually.

Uses:

(1) Perforated basket centrifuge is extensively used for separating crystalline drugs (such as aspirin) from the mother liquor. Free flowing product can be obtained because mother liquor is removed completely.

(2) It is also used for removing unwanted solids from a liquid. For example, precipitated proteins are removed from insulin.

(3) Sugar crystals are separated using perforated basket centrifuge.

Advantages:

(1) The centrifuge is very compact and it occupies very little floor space.

(2) It can handle slurries with a high proportion of solids and even those having paste like consistency.

(3) The final product has very low moisture content.

(4) In this method, the dissolved solids are separated from the cake.

(5) The process is rapid.

Disadvantages:

(1) The entire cycle is complicated resulting in considerable labour costs.

(2) It is a batch process.

(3) If the machine is adapted for prolonged operation, there is considerable wear and tear of the equipment. On prolonged operation, the solids may form hard cake, due to the centrifugal force, which is difficult to remove simultaneously.

Variants : For the separation of fine crystals, the perforations of 3 mm in diameter are sufficient. But for finely ground materials, the basket is lined with fine meshed gauze or with a cloth supported on a coarser gauge.

Non-perforated Basket Centrifuge

Principle : This is a sedimentation centrifuge. The separation is based on the difference in the densities of solid and liquid phases without a porous barrier. The bowl contains a non-perforated side-wall. During cen-

trifugation, solid phase is retained on the sides of the basket, while the liquid remains at the top, which is removed by a skimming tube.

Construction : The construction of a under-driven non-perforated basket centrifuge is shown in Figure 11-6. It consists of a basket, which may be made of steel or any other suitable metal. The basket is suspended on vertical shaft and is driven by a motor using a suitable power system.

Working : The suspension is fed continuously into the basket. During centrifugation, solid phase is retained on the sides of the basket, while liquid remains on the top. The liquid is removed over a weir or through a skimming tube (Figure 11-6). When a suitable depth of solids has been deposited on the walls of the basket, the operation is stopped. The solids are then scraped off by hand or using a scraper blade.

Uses : Non-perforated basket centrifuge is useful when the deposited solids offer high resistance to the flow of liquid.

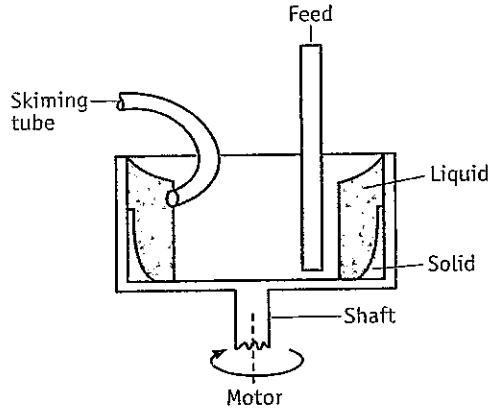


Figure 11-6. Construction of non-perforated basket centrifuge.

Variants : When a mixture of liquids is to be separated, the denser liquid is collected near the walls and the lighter liquid forms an inner layer. Overflow weirs are arranged so that the two constituents are continuously removed.

Semi-continuous Centrifuge or Short Cycle Automatic Batch Centrifuge

Principle : Semi-continuous centrifuge is a filtration centrifuge. The separation is through a perforated wall based on the difference in the densities of solid and liquid phases. The bowl contains a perforated side-wall. During centrifugation, the liquid phase passes through the perforated wall, while solid phase retains in the bowl. The solid is washed and removed

by cutting the sediment using a blade. It is a short cycle automatic batch centrifuge.

Construction : The construction of a semi-continuous centrifuge is shown in Figure 11-7. It consists of a vertical perforated basket, which is supported from a horizontal shaft driven by a motor. From the open side of the basket, provisions are made at the centre to introduce feed and wash pipe through horizontal tubes. A feeler (not shown) rides over the feed, which is connected to diaphragm valve through air supply. The feeler controls the thickness of the feed. Hydraulic cylinder attachment is made in such a manner that the discharge chute enters from the sides of basket, when discharge of crystals is desirable.

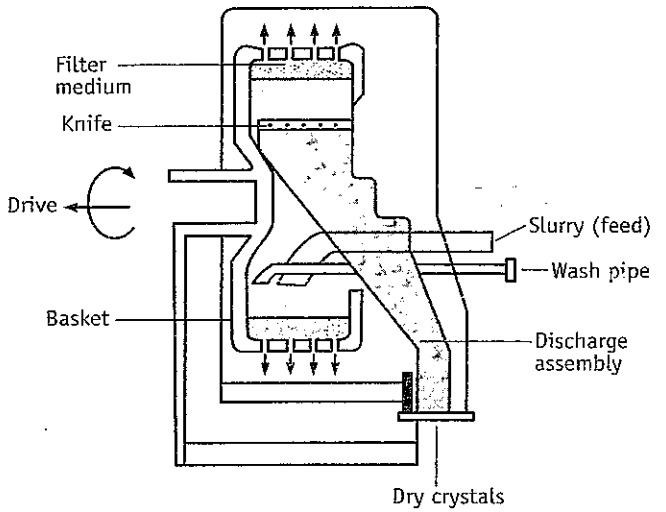


Figure 11-7. Construction of semi-continuous centrifuge.

Working : The perforated basket is allowed to rotate and slurry is introduced from the side pipe. During centrifugation, the slurry passes through the perforated wall. The solids are retained in the basket, while filtrate leaves the basket, which is collected at outlet. Further, the cake is washed with water. The wash escapes from the basket through the filtrate outlet.

After achieving the desired thickness (50 to 70 mm), the feeler cuts off the air supply to a diaphragm valve that automatically shuts off the entry of slurry. The hydraulic cylinder is actuated, which lifts the knife along with the discharge chute. The knife does not cut the cake completely down to the screen, but leaves a layer of crystals that acts as a filter medium for further separation in the next cycle. The residual crystals may be given a brief wash before starting the next cycle.

Through a timer and air supply mechanisms, diaphragm valves controls all steps. Therefore, the entire cycle is semiautomatic. The discharged crystals may contain 2 to 4 % of moisture.

Advantages : Short-cycle automatic batch centrifuge is used when solids can be drained fast from the bowl.

Disadvantage : During discharge, considerable breakage of crystals is possible. Many moving parts are involved making the construction and functioning more complicated.

Horizontal Continuous Centrifuge

Principle : This is a sedimentation centrifuge. The separation is based on the difference in the densities of solid and liquid phases without a porous barrier. When slurry is introduced through the shaft of the screw element into conical bowl, sedimentation of solids takes place due to centrifugal action. The solids are lifted up by the screw element, while the liquid phase is continuously drained.

Construction : The construction of a horizontal continuous centrifuge is shown in Figure 11-8. It consists of a cylindrical or conical bowl mounted horizontally and capable of rotating at 50 to 65 revolutions per second. The bowl has a diameter of about 0.5 m. Within the bowl, a screw conveyor is placed which rotates in the same direction as the bowl, but at a slightly slower speed.

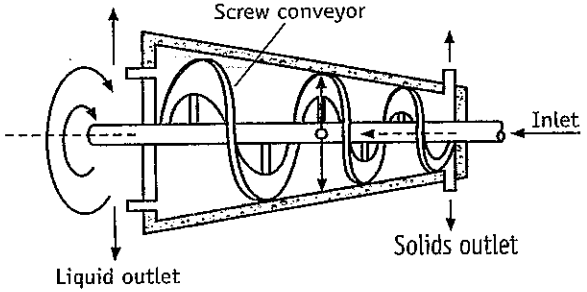


Figure 11-8. Construction of the horizontal continuous centrifuge.

Working : The bowl and the screw conveyor are allowed to rotate using suitable power supply. The slurry is introduced through the shaft as shown in Figure 11-8. The liquid moves into the wider portion of the bowl. Sedimentation of solids takes place due to centrifugal action. The solids are lifted by the screw element, while the liquid phase is continuously drained. The solid material is carried towards outlet by the conveyor and is discharged continuously. The solids are conveyed to a dry 'beach' where they get dried.

Uses : Horizontal continuous centrifuge is used when a high proportion of solids is present in the slurry.

Advantages : (1) Continuous horizontal centrifuge is very flexible in operation.

(2) It is capable of handling solids as large as 10 to 15 mm or as small as a few microns.

(3) It can be used for slurries with concentrations ranging from 0.5 to 50 %.

Variants : The conical form as shown in Figure 11-8 is in common use, but some materials are difficult to convey when dry, for example, if the material is soft and compressible. In such cases, a cylindrical bowl is used with a short conical section near the outlet. As a result, the solid is submerged in the liquid for most of the time and is separated only when it is near the discharge point.

Supercentrifuge

Sharples supercentrifuge is a continuous centrifuge used for separating two immiscible liquid phases.

Principle : Supercentrifuge is a sedimentation centrifuge. The separation is based on the difference in the densities between two immiscible liquids. Centrifugation is done in the bowl of small centrifuge. During centrifugation, the heavier liquid is thrown against the wall, while the lighter liquid remains as an inner layer. The two layers are simultaneously separated using modified weirs.

Construction : The construction of a supercentrifuge is shown in Figure 11-9. It consists of a long hollow cylindrical bowl of small diameter. It is suspended from a flexible spindle at the top and guided at the bottom by loose-fit bushing. It can be rotated on its longitudinal axis. Provision is made at the bottom for the feed inlet using pressure system. Two liquid outlets are provided at different heights at the top of the bowl, and modified weirs, are attached.

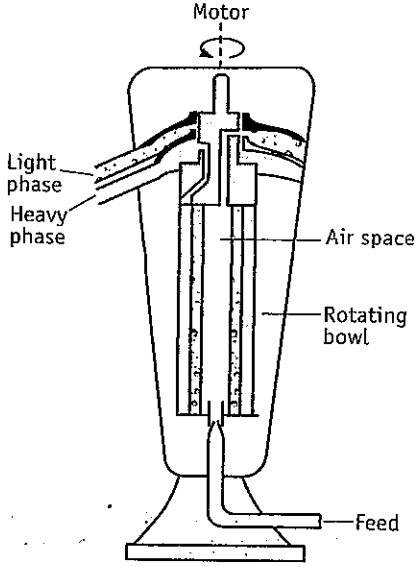


Figure 11-9.
Construction of supercentrifuge.

Working : The centrifuge is allowed to rotate on its longitudinal axis at a high speed, usually about 2000 revolutions per minute with the help of drive-assembly. The feed is introduced from the bottom of the centrifuge using a pressure system. During centrifugation, two liquid phases separate based on the difference in their densities. The heavier liquid is thrown against the wall, while the lighter liquid forms an inner layer. Both liquids rise to the top of the vertical bowl.

The liquid-liquid interface (the so-called neutral zone) is maintained by an hydraulic balance. These two layers are simultaneously removed as two liquids separately from different heights through modified weirs (as shown in Figure 11-9). Thus the supercentrifuge can work for continuous separation of immiscible liquid phases.

Use : Supercentrifuge is used for separating liquid phases of emulsions in foods and pharmaceuticals.

Variants : *Tubular bowl centrifuge* : It is used to separate solids and liquids, when the solid content is low. It is a cylindrical bowl and other facilities remain the same. During centrifugation, clear liquid overflows from the weir at the top, solids are deposited on the wall and are removed at intervals, if necessary. Capacity of this centrifuge is limited.

Conical Disc Centrifuge or De Laval Clarifier

As it is a clarifier, solids or immiscible liquids are present in low concentration in the feed. Complete clarification of the feed is possible by centrifugal means.

Principle : It is a sedimentation centrifuge. The separation is based on the difference in the densities between the phases under the influence of centrifugal force. In this, a number of cone-shaped plates are attached to a central shaft (which has the provision for feed) at different elevations. During centrifugation, the dense solids are thrown outwards to the underside of the cone shaped casing, while the lighter clarified liquid passes over the bowl and recovered from the top of the cone.

Construction : The construction of a conical disc centrifuge is shown in Figure 11-10. It consists of a shallow form of bowl containing a series of conical discs attached to the centre shaft at different elevations. The discs are made up of a thin sheet of metal or plastic separated by narrow spaces. Matching holes in the discs (about half way between the axis and the wall of the bowl) form channels through which the liquid passes. A concentric tube is placed surrounding the central drive shaft.

Working : Centrifuge is allowed to rotate. Low speed and short time of centrifugation is sufficient to give high degree of clarification. The feed is introduced through the concentric tube surrounding the shaft. The feed

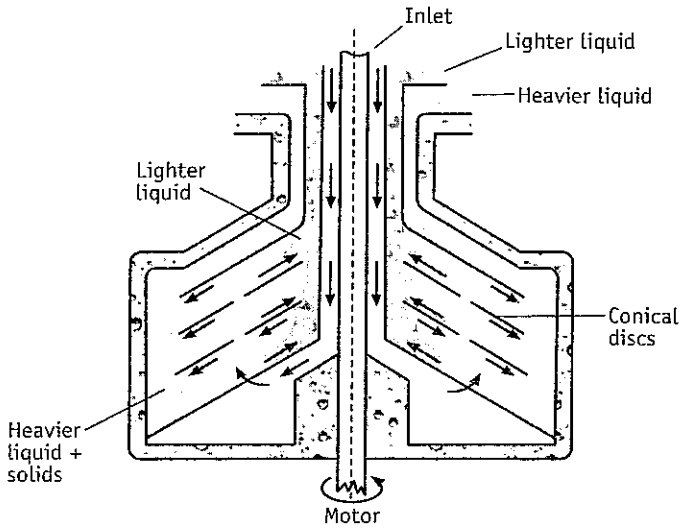


Figure 11-10. Construction of the conical disc centrifuge.

flows down and enters into the spaces between the discs (shown by the arrows). During centrifugation, the liquid flows into the channels (holes at the centre of the disc) and upward past the discs. These substances move along the surfaces of the discs to the limits of the inner and outer layers. The solids and heavy liquids are thrown outward and move underside of the discs.

Then the solids deposit at the bottom of the cone, which is removed intermittently. The lighter liquid moves to the upper side of the discs. The liquid raises to the top and escapes from the outlet.

Uses:

(1) Two immiscible liquids can be easily separated by a continuous process after liquid/liquid extraction as in case of manufacture of antibiotics.

(2) Suspensions containing low concentration of solids can be separated quickly. Solids that are gelatinous or slimy can be separated by disc cone centrifuge. Such substances may plug the filter in other methods.

(3) Starch is collected after washing and purification stages.

(4) In the manufacture of insulin, the liquor is clarified to remove the precipitated proteins.

(5) Concentration of one fluid phase is possible as in the separation of cream from milk, concentration of rubber latex, removing solids from lubricating oils, inks and beverages.

Advantages:

(1) Conical disc centrifuges are compact occupying a very small space.

(2) The separating efficiency is very high, so that the particles are deposited very rapidly. It is suitable, if the sediment is a fluid deposit or sludge.

(3) By controlling the speed of rotation and rate of flow, particles are separated into two size fractions.

Disadvantages:

(1) The construction of a conical disc centrifuge is complicated.

(2) Its capacity is limited.

(3) It is not suitable if the sediment of solids forms a hard cake.

Comment 11-8. Centrifugal separation is a batch process. True of false. Justify.

Comment 11-9. How can the centrifugal effect be effectively applied for separation?

Comment 11-10. Suggest a centrifuge when a large volume of material needs to be handled?

Summary

Centrifugation is a separation technique with the aid of centrifugal force. Centrifugation technique is used to separate crystalline drugs from mother liquor, proteineous drugs and macromolecules present in colloidal dispersions, separation of drugs from blood, tissue and urine. It is also used for evaluation of the physical stability of suspensions and emulsions and the determination of molecular weight. Normally, sedimentation process also gives the separation which involves gravitational force. In centrifugation, the gravitational force is replaced by centrifugal force. Centrifugation is particularly useful when separation by filtration is difficult. The equipment used for this purpose are known as centrifuges. The speed of the centrifugation is expressed by rpm or G and is critical for the separation. Centrifuges are classified as sedimentation centrifuges and filtration centrifuges. In the sedimentation centrifuge, the difference in the densities of the two phases is the deciding factor. In filtration centrifuge, a porous medium is used through which the liquid gets separated from the solid. Normally, a perforated wall such as canvas or metal cloth is covered with a filter medium.

Colloidal particles are difficult to sediment, because gravitation force is not adequate. A stronger force such a centrifugal force is necessary for the separation. Such a parameter is known as separating power. The theory of centrifugation is based on the particle size and its influence for separation. The centrifugal effect is expressed as a ratio of centrifugal force to gravitating force. The centrifugal effect is directly proportional to the diameter and square of speed of rotation. For obtaining increased centrifugal effect, the size should be smaller and the speed must be higher. Based on these principles, the size of the centrifuge, i.e. diameter of the centrifuge tubes is chosen. Thus, the theory permits the selection of right dimensions of centrifuge. The factors affecting the centrifugation are: the nature of slurry, flow of slurry, centrifuge dimensions. In addition, time of centrifugation is a process parameter, particularly for batch type centrifuges.

Industrial centrifuges are available in different designs, each meets a specific requirement of the slurry and end product. A bowl or basket is used in which the slurry gets separated into two different phases. These equipment are driven by a suitable motor. Some the industrial centrifuges are: perforated basket centrifuge, non-perforated basket centrifuge, short-cycle automatic batch centrifuge, continuous horizontal centrifuge, supercentrifuge and conical disc centrifuge. For continuous centrifugation, a screw conveyor would be ideal or a tall cylindrical bowl with narrow diameter is useful.

Glossary of Symbols

C = Centrifugal effect, m/s^2.
d = Diameter of the rotation, m.
F = Centrifugal force, N.
G = Gravitation force, N.
g = Acceleration due to gravity, m/s^2.
m = Mass of the body, kg.
n = Speed of the rotation, revolutions per second.
r = Radius from the centre to the moving body in a circular path, m.
v = Velocity of the moving body, m/s.
RCF = Relative centrifugal force.

QUESTION BANK

Each question carries one mark

Note : Encircle the alphabet which corresponds to the single best response.

1. If the amount of materials to be processed is huge and a low centrifugal effect is sufficient, then one of the following is economical to use.
   A. Large centrifuge operating at high speed
   B. Large centrifuge operating at low speed
   C. Small centrifuge operating at high speed
   D. Small centrifuge operating at low speed
2. Which is the principle difference (in the properties) that influences centrifugation?
   A. Densities
   B. Interfacial tensions
   C. Particle sizes
   D. Viscosities

Advantages:

(1) Conical disc centrifuges are compact occupying a very small space.

(2) The separating efficiency is very high, so that the particles are deposited very rapidly. It is suitable, if the sediment is a fluid deposit or sludge.

(3) By controlling the speed of rotation and rate of flow, particles are separated into two size fractions.

Disadvantages:

(1) The construction of a conical disc centrifuge is complicated.

(2) Its capacity is limited.

(3) It is not suitable if the sediment of solids forms a hard cake.

Comment 11-8. Centrifugal separation is a batch process. True of false. Justify.

Comment 11-9. How can the centrifugal effect be effectively applied for separation?

Comment 11-10. Suggest a centrifuge when a large volume of material needs to be handled?

Summary

Centrifugation is a separation technique with the aid of centrifugal force. Centrifugation technique is used to separate crystalline drugs from mother liquor, proteineous drugs and macromolecules present in colloidal dispersions, separation of drugs from blood, tissue and urine. It is also used for evaluation of the physical stability of suspensions and emulsions and the determination of molecular weight. Normally, sedimentation process also gives the separation which involves gravitational force. In centrifugation, the gravitational force is replaced by centrifugal force. Centrifugation is particularly useful when separation by filtration is difficult. The equipment used for this purpose are known as centrifuges. The speed of the centrifugation is expressed by rpm or G and is critical for the separation. Centrifuges are classified as sedimentation centrifuges and filtration centrifuges. In the sedimentation centrifuge, the difference in the densities of the two phases is the deciding factor. In filtration centrifuge, a porous medium is used through which the liquid gets separated from the solid. Normally, a perforated wall such as canvas or metal cloth is covered with a filter medium.

Colloidal particles are difficult to sediment, because gravitation force is not adequate. A stronger force such a centrifugal force is necessary for the separation. Such a parameter is known as separating power. The theory of centrifugation is based on the particle size and its influence for separation. The centrifugal effect is expressed as a ratio of centrifugal force to gravitating force. The centrifugal effect is directly proportional to the diameter and square of speed of rotation. For obtaining increased centrifugal effect, the size should be smaller and the speed must be higher. Based on these principles, the size of the centrifuge, i.e. diameter of the centrifuge tubes is chosen. Thus, the theory permits the selection of right dimensions of centrifuge. The factors affecting the centrifugation are: the nature of slurry, flow of slurry, centrifuge dimensions. In addition, time of centrifugation is a process parameter, particularly for batch type centrifuges.

Industrial centrifuges are available in different designs, each meets a specific requirement of the slurry and end product. A bowl or basket is used in which the slurry gets separated into two different phases. These equipment are driven by a suitable motor. Some the industrial centrifuges are: perforated basket centrifuge, non-perforated basket centrifuge, short-cycle automatic batch centrifuge, continuous horizontal centrifuge, supercentrifuge and conical disc centrifuge. For continuous centrifugation, a screw conveyor would be ideal or a tall cylindrical bowl with narrow diameter is useful.

Glossary of Symbols

C = Centrifugal effect, m/s^2.
d = Diameter of the rotation, m.
F = Centrifugal force, N.
G = Gravitation force, N.
g = Acceleration due to gravity, m/s^2.
m = Mass of the body, kg.
n = Speed of the rotation, revolutions per second.
r = Radius from the centre to the moving body in a circular path, m.
v = Velocity of the moving body, m/s.
RCF = Relative centrifugal force.

QUESTION BANK

Each question carries one mark

Note : Encircle the alphabet which corresponds to the single best response.

1. If the amount of materials to be processed is huge and a low centrifugal effect is sufficient, then one of the following is economical to use.
   A. Large centrifuge operating at high speed
   B. Large centrifuge operating at low speed
   C. Small centrifuge operating at high speed
   D. Small centrifuge operating at low speed
2. Which is the principle difference (in the properties) that influences centrifugation?
   A. Densities
   B. Interfacial tensions
   C. Particle sizes
   D. Viscosities

3. Centrifugal method is used for one of the following process.
   A. Mixing
   B. Purification
   C. Separation
   D. Sizing
4. Centrifugal effect counter-acts one of the following forces.
   A. Brownian forces
   B. Cohesive forces
   C. Electrostatic forces
   D. Gravitational forces
5. Which of the following centrifuges works against the gravitation acceleration?
   A. Conical disc centrifuge
   B. Continuous horizontal centrifuge
   C. Perforated basket centrifuge
   D. Semi-continuous centrifuge
6. The solid that has high specific gravity remains in one of the following states in the centrifuge tube, once centrifugation is completed.
   A. Bottom
   B. Middle
   C. Top
   D. Uniform
7. Which one of the following forces greatly enhances the separation forces?
   A. Brownian forces
   B. Centrifugal forces
   C. Gravitational forces
   D. Van der Waals forces
8. Centrifugal effect is expressed in one of the following ratios.
   A. Centrifugal force to density of liquid
   B. Centrifugal force to gravitational force
   C. Centrifugal force to sedimentation force
   D. Gravitation force to sedimentation force
9. What are the two factors responsible for separation by centrifugation?
   A. Density and sedimentation force
   B. Density and speed of rotation
   C. Diameter and speed of rotation
   D. Speed of rotation and sedimentation force
10. Centrifugation is useful in one of the following types of dispersions.
    A. Coarse dispersions
    B. Colloidal dispersions
    C. Molecular dispersions
    D. Multi-size dispersions
11. For a sedimentation type, the centrifuge has one of the following conditions.
    A. Basket is non-perforated
    B. Basket is perforated
    C. Containing filter aid
    D. Containing filter medium
12. Washing of solids is NOT possible in one of the following centrifuges.
    A. Non-perforated basket centrifuge
    B. Perforated basket centrifuge
    C. Semi-continuous centrifuge
    D. Super-centrifuge

13. Conical disc centrifuge works on one of the following mechanisms of separation.
    A. Clarification
    B. Filtration
    C. Gravity separation
    D. Sedimentation
14. Continuous horizontal centrifuge consists of one of the following parts.
    A. Filter cloth
    B. Knife
    C. Screw element
    D. Weirs
15. Weirs are employed in centrifugation process for one of the following purposes.
    A. Adding water for washing
    B. Preventing air entrapment
    C. Removing liquid
    D. Separating solids
16. Centrifuges are used for the analysis of dosage forms in terms of one of the following stabilities.
    A. Chemical stability
    B. Photostability
    C. Physical stability
    D. Thermal stability
17. Which one of these is the gravitational constant in SI units (m/s^2)?
    A. 0.09807
    B. 0.9807
    C. 9.807
    D. 98.07
18. The velocity of centrifuge is commonly expressed in terms of the following units.
    A. Diameter of the rotation
    B. Meter per second square
    C. Metre square per second
    D. Revolutions per minute
19. Which is the example of batch type centrifuge?
    A. Conical disc centrifuge
    B. Horizontal centrifuge
    C. Perforated basket centrifuge
    D. Supercentrifuge
20. Which one of the following is an under-driven centrifuge?
    A. Horizontal continuous centrifuge
    B. Perforated basket centrifuge
    C. Semi-continuous centrifuge
    D. Conical disc centrifuge
21. During discharge, breaking of crystals is possible in one of the following centrifuges.
    A. Horizontal continuous centrifuge
    B. Non-perforated basket centrifuge
    C. Semi-continuous centrifuge
    D. Super-centrifuge
22. Which factor does NOT affect the separation process of a centrifuge?
    A. Centrifugation time
    B. Nature of slurry
    C. Speed of centrifuge
    D. Temperature

23. Which one of the following is a filtration centrifuge?
    A. Conical disc centrifuge
    B. Continuous horizontal centrifuge
    C. Perforated basket centrifuge
    D. Super-centrifuge
24. De Laval clarifier is used for:
    A. Centrifugation
    B. Clarification
    C. Filtration
    D. Sedimentation
25. Bacterial enzymes are prepared by removing bacteria. Suggest the possible method of separation.
    A. Filtration centrifuge
    B. Perforated centrifuge
    C. Sedimentation centrifuge
    D. Vacuum filter

Each question carries 2 marks

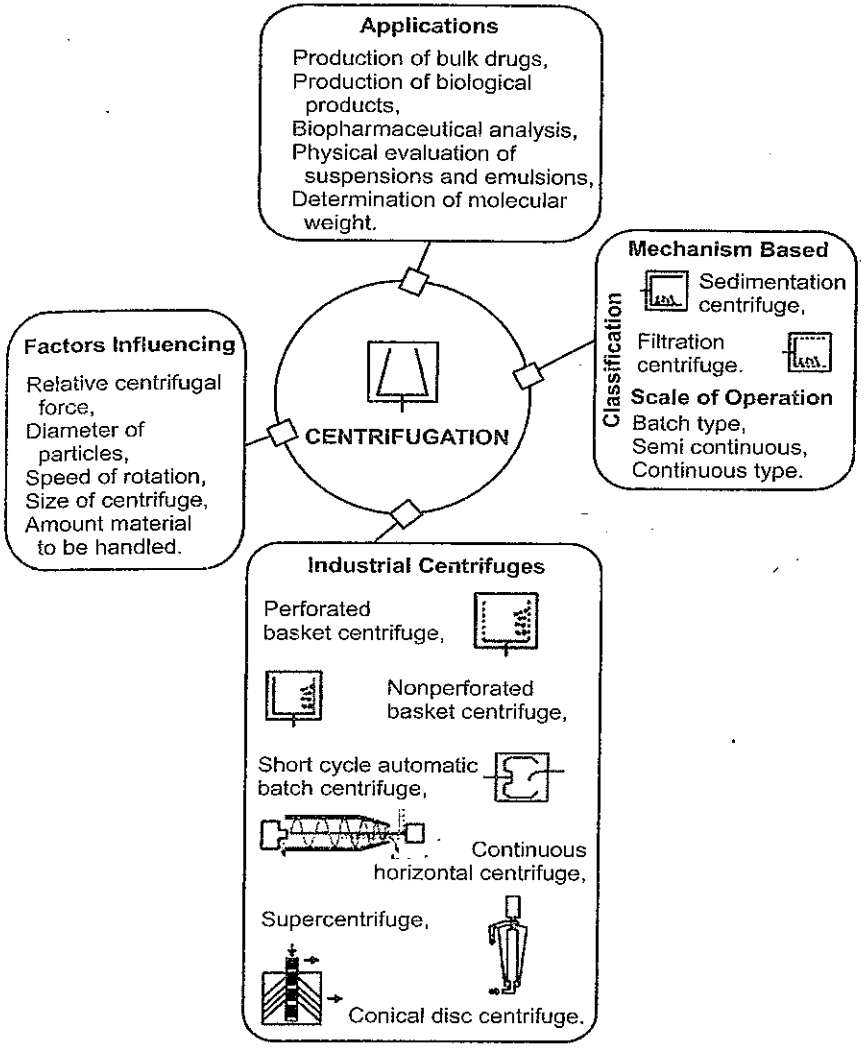
1. Write two pharmaceutical applications of centrifugal sedimentation.
2. What are basket centrifuges? Describe their applications.
3. Write the applications of perforated basket centrifuges.
4. Explain the principle behind centrifugal separation.
5. What is meant by under-driven filtration type basket centrifuges?

Each question carries 5 marks

1. Classify industrial centrifuges. Write construction and working of a perforated basket centrifuge.
2. Give five pharmaceutical applications of centrifugal separations.
3. Describe continuous centrifuges, giving their advantages.
4. Describe the construction and working of a Sharples supercentrifuge.
5. Describe the theory of centrifugation.

Each question carries 10 marks

1. Discuss construction and working of a discontinuous centrifuge for solid separation.
2. Describe the construction and working of a centrifuge used for the separation of slurry containing high percentage of solids.
3. Describe the construction and working of a centrifuge used for the separation of two liquid phases as in case of emulsions.



MIND MAP OF CENTRIFUGATION

CHAPTER 12

Materials of Construction

Factors Influencing Selction of Materials
Classification of Materials for Plant Construction
Ferrous Metals
Non-Ferrous Metals
Nonmetals—Inorganic
Nonmetals—Organic

LEARNING OBJECTIVES

After reading this chapter, the reader should be able to:

- Appreciate the nature and properties of materials employed in the design of equipment.
- Explain the factors influencing the selection of materials.
- Review the classification of materials used for construction of equipment that permits the easy understanding of the properties.
- Analyze the use of ferrous and non-ferrous metals as material of construction.
- Highlight the use of glass, rubber and plastic as a component parts in handling dosage forms.

A number of equipment are used in the manufacture of pharmaceuticals, bulk drugs, antibiotics, biological products, etc. In addition, several accessories such as containers for processing and packing of finished products are essential. A wide variety of materials can be utilised for the construction of equipment. The success or failure of a new chemical plant or in the improvement of an existing facility depends on:

1. Design of equipment
2. Selection of material
3. Technique of fabrication

The design (construction) and working of equipment employed in unit operations have been discussed vividly in various chapters. The knowledge on the properties of materials is essential for selecting the right kind of materials.

The purpose of this chapter is to provide a working knowledge on some of the major types of materials available for construction. This will determine whether a process is expensive or complex. It also decides the profit and utility of the end product. The technical details on the fabrication are not within the scope of this chapter, because it needs special expertise, which may not be relevant.

The selection of a material for the construction of equipment depends on the following properties.

1. Chemical resistance
2. Structural strength
3. Resistance to physical shock i.e. operating pressure
4. Resistance to thermal shock i.e. operating temperature
5. Ease of fabrication
6. Cost
7. Maintenance

Selecting satisfactory materials for the construction of plant encounters problems involving chemical, physical and economic factors.

FACTORS INFLUENCING SELECTION OF MATERIALS

Chemical Factors

The container or equipment should protect the integrity of the contents. At the same time, the contents should not alter the properties of the material with which the vessel is made. When these are in contact with each other, the effects may be understood in two ways:

(a) The contents may react and thus get contaminated with the material of the plant.

(b) The drugs and chemicals may destroy the material of the plant.

Contamination of the product : The impurities in chemical substances or bulk drugs may be from different sources. The solvent action may cause corrosion, so that the traces of metal ions used in construction tend to pass into solution and contaminate the product. Substances such as glass, silica, lead, cast iron, steel, tinned iron and a variety of alloys are used in the construction of a chemical plant and most of them produce contamination.

Even though impurities are present in traces, these may cause the product to decompose. For example, heavy metals inactivate penicillin. The appearance of the product may also be effected by changes in colour. Glass vessels may give up traces of alkali to the solvent, though this is unlikely, if the vessels are of hard glass. Sometimes, product contamination may be innocuous and non-toxic.

Influence of chemicals on the material of the plant : The solutions that come into contact with the equipment are generally corrosive in nature. In addition, equipment are exposed to extremes of pH, temperatures and pressures. As a result, the material gets corroded, losing its strength and durability. Therefore, the life of the equipment is reduced.

The knowledge of materials of plant construction assists greatly in providing a plant that will be resistant to attack of acids, alkalis, oxidizing agents, tannins, etc. New alloys having special physical and chemical properties have been developed to meet the problems of chemical reactions.

Physical Factors

Strength : The material should have sufficient strength so that it can withstand the stresses or rigours to which the material is subjected in the production. Iron and stainless steel can satisfy these properties. For example, in the compression of tablets, the dies and punches should have sufficient mechanical strength to transmit the applied pressure, otherwise tablets are poorly formed. Glass satisfies the property of strength, but is breakable.

Generally tablets, capsules and vials are preserved in blister packing. The packing materials should withstand the rigors of handling, shipment and transportation. Plastic materials are used, because these offer sufficient mechanical strength.

Aerosol containers must withstand pressure as high as 960 kPa to 1.20 MPa at 55 °C. Tin plate containers can satisfy this condition, while plastic containers cannot be used due to its poor mechanical strength.

Mass : Many times, the equipment should be transported or moved from one place to another. This is possible when the material is light in weight, when other factors are satisfactory. Similarly, plastic material is employed for the manufacture of containers for use of pharmaceuticals and cosmetics on account of its light weight. As a result the cost of transportation reduces.

Wear properties : These properties become important, when there is a possibility of friction between the moving parts. For example, during milling and grinding, the grinding surfaces wear off and these materials will be incorporated into powder as impurities. Such type of mills should be avoided, when drugs of high purity are required. The risk of contamination is more due to wear of ceramic or iron equipment (sieves).

During tabletting operations, the upper and lower punches rotate continuously. In this process, the wearing of these punches is high.

Thermal conductivity : In chemical industries, several equipment such as evaporators, dryers, stills and heat exchangers are used. The material employed for their fabrication should have good thermal conductivity. However, the resistant films greatly retard the process of heat transfer. For example, iron, glass or graphite tubes are used in the fabrication of heat exchangers, so that effective heat transfer is possible.

Thermal expansion : If the material has high coefficient of expansion, the design of plants may be greatly complicated. This increases stresses and the risk of fracture when temperature changes. The material should be able to maintain size and shape of equipment at working temperatures.

Ease of fabrication : During fabrication, the materials undergo various processes such as casting, welding, forging and machinisation, etc. For example, glass and plastics can be easily moulded into containers of different shapes and sizes. Glass can be used as a lining material for reaction vessels used in the chemical industry. Iron and steel undergo various rigours of processing during fabrication.

Cleansing : Smooth and polished surfaces allow the process of cleansing easy. Materials that can be obtained with such a finishing are ideal, when scrupulous cleanliness is necessary. For example, stainless steel and glass are suitable for this purpose.

Sterilisation : In the production of parenterals, ophthalmic products, antibiotics and biologicals, sterilisation is an essential step, which is obtained by autoclaving. The material should be capable of withstanding the necessary treatment, usually steam and pressure. In most cases, cleansing is a preliminary step to the sterilisation of apparatus and plant. For example, equipment and vessels are made of stainless steel, because they can be sterilised.

Transparency : Transparency may be a useful property because it permits the visual observation of the changes during a process. For this reason, borosilicate glass has been increasingly used in the construction of reactors, fermentors, etc.

Economic factors : Initial costs and maintenance of the plant must be economical. Here the main concern is not simply to obtain the least cost material. Low wearing qualities and lower maintenance may well mean that a higher initial cost is more economical in the long run.

CLASSIFICATION OF MATERIALS FOR PLANT CONSTRUCTION

Materials of pharmaceutical plant construction can be classified as shown in Figure 12-1. Different materials and their properties are discussed so that right kind of materials can be selected for the desired purpose and function.

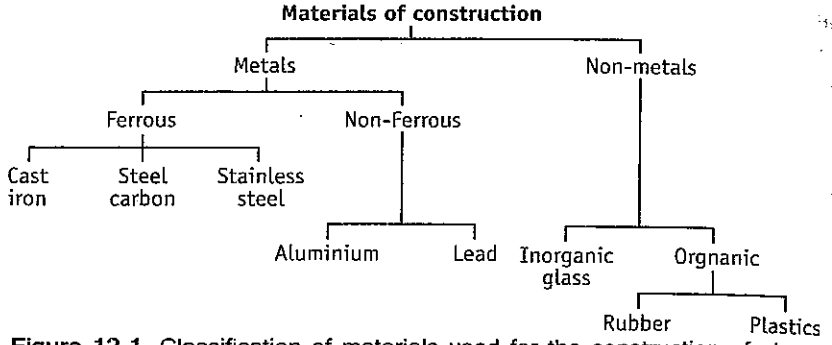


Figure 12-1. Classification of materials used for the construction of plant.

FERROUS METALS

Iron metal is one of the widely used materials for the construction of plants because of its mechanical strength, abundant availability and lower cost. Some varieties of iron are discussed.

Cast Iron

Cast iron consists of iron with a proportion of carbon (beyond 1.5 %). The properties of iron depend on the amount of carbon present in it. Cast iron is abundantly available, inexpensive and therefore widely used. A number of types of cast iron are available (Table 12-1).

TABLE 12-1
Different Types of Cast Iron Alloys

Types of cast iron	*Composition*	*Properties*	*Disadvantages*
Gray cast iron	Carbon silicon	Low cost, easy to cast into intricate shapes and linings. For grinding balls, dies, impellers.	Brittle, poor resistance to impact and shock
Maleable iron	white cast iron carbon–2.5 %	Corrosion resistant Type I easy to machine	Type II less easy to machine
High silicon cast iron	Silicon–13-16 % cast iron	Resistant to corrosion, oxidising environment, reducing environment. Used in sulphuric acid services.	Not easily machined and welded
Nickel resistant cast iron		Superior toughness, impact resistant, easy to weld and machine. Corrosion resistant and heat resistant.	Oxidising agents such as nitric acid are highly detrimental. There is little attack from neutral or alkaline solution

Advantages : (1) Cast iron is cheap. Therefore, it is used in place of expensive plant material with coatings or linings of enamel or plastic.

(2) It is resistant to concentrated sulphuric acid, nitric acid and dilute alkalis.

(3) Since cast iron has low thermal conductivity, it is used for the construction of outer surface of jackets of steam pans.

Disadvantages : (1) Cast iron is very hard and brittle. Therefore, it is difficult to machine. This disadvantage can be overcome by the addition of different materials to improve its performance.

(2) Cast iron is attacked by dilute sulphuric acid, dilute nitric acid and dilute as well as concentrated hydrochloric acid.

(3) Since cast iron has low thermal conductivity, it cannot be used for heat transfer in stills.

Uses : It is commonly used for the construction of:

(1) Supports for plant

(2) Jackets of steam pans

(3) Linings with enamel, plastic or suitable protective material

Modifications of cast iron : Cast iron is not considered corrosion resistant. The characteristics of cast iron can be altered by alloying with other elements such as silicon, nickel and chromium (Table 12-1).

Commercial Types : Duriron and Durichlor.

Carbon Steel or Mild Steel

Carbon steel is an iron alloy, which contains only a small percentage of carbon. Advantages of carbon steel are:

(1) Carbon steel is cheapest. Therefore, it is preferred.

(2) It is easily weldable and is frequently used in fabrication.

Disadvantages of carbon steel are:

(1) Carbon steel has limited resistance to corrosion. This property can be improved by preparing alloys.

(2) It reacts with caustic soda, brine and sea-water. Alloying it can reduce this reactivity.

Uses : Carbon steel is used for the construction of bars, pipes and plates. It is used to fabricate large storage tanks for water, sulphuric acid, organic solvents, etc. It is used for supporting structures such as grinders and bases for plant vessels.

Variants of carbon steel : The properties of carbon steel can be altered by alloying it with other metals. Some of the metals and their properties are given below:

Nickel (Ni)	improves toughness, corrosion resistance and low temperature properties.
Chromium (Cr)	increases hardness, more abrasive resistance and resistance to oxidation.
Silicon (Si)	increases hardness, more abrasive resistance and resistance to oxidation.
Molybdenum (Mb)	provides strength at elevated temperatures

The types of alloys of carbon steel are given in Table 12-2.

TABLE 12-2
Different Types and Alloys of Carbon Steel

Variety of carbon steel	*Composition*	*Advantages*
Low alloy steel	Low concentration of iron, carbon, manganese, nickel, chromium and molybdenum	❖ High mechanical strength ❖ Corrosions resistant to environments. ❖ Walls of plant can be thin.
Alloying with nickel	Nickel	❖ Increased hardness ❖ High corrosion resistance ❖ Improved low temperature properties.
Alloying with silicon chromium	Nickel chromium	❖ Abrasion resistant ❖ Corrosion resistant ❖ Resistant to oxidation

Stainless Steel

Stainless steel is an alloy of iron. Usually, it contains chromium and nickel, which make the steel corrosion resistant. Stainless steel is stabilised by the addition of titanium, niobium or tantalum. Minor amounts of other elements such as copper, molybdenum and selenium are added. Stainless steel also has the advantage of ease in fabrication.

The abundant use of stainless steel is due to the properties such as:

- ❖ heat resistance
- ❖ corrosion resistance
- ❖ ease of fabrication
- ❖ cleaning and sterilisation
- ❖ tensile strength

Depending on the composition, stainless steel alloys are available in three groups, viz., martensitic, ferritic and austenitic. These are given in Table 12-3.

TABLE 12-3
Different Types of Stainless Steel

Composition	*Advantages*	*Disadvantages*	*Uses*
Martensitic (e.g. Type 410)			
Chromium: 12-20 % Carbon: 0.2- 0.4 % Nickel upto 2.0 %	Mildly corrosion resistant, atmospheric and organic exposures	Ductility is poor	Sinks, bench tops, storage tanks, buckets, mixing elements etc.
Ferritic (α-form) (e.g. Type 430)			
Chromium: 15-30 % Carbon: 0.1 % Nickel: nil	Better corrosion resistant; easy to machine; resistant to oxidation and temperature. (upto 800 °C)	not good against reducing agents, hydrochloric acid	Tower linings, baffles, separator, tower, heat exchanger, tubings, condensers, furnace parts, pumps shafts, valve parts.
Austenitic (γ-form)			
Chromium: 13-20 % Nickel: 6-22 % Carbon: 0.1 % < 0.25 %	Highly corrosion resistant; readily cleaned; steriliz able; easy to weld; non-magnetic	Not easy to machine	Fermenters, storage vessels, evaporators, extraction vessels, small apparatus (funnels, buckets etc.)

Comment 12-1. Why is stainless steel used instead of steel (iron) for the fabrication of equipment?

Comment 12-2. Austenitic steel is frequently used for the fabrication the equipment. Why?

Comment 12-3. High coefficient of thermal expansion of metal is not necessary for the metal used in designing the equipment. True or false. Justify.

NON-FERROUS METALS

Aluminium

A number of aluminium items are used in regular day to day life. Aluminium is cheap, light in weight and offers adequate mechanical strength. In addition, aluminium equipment can be easily fabricated. Further, aluminium can be strengthened by cold working. Their maintenance and cleaning is also easy. Hence, its utility is mostly recommended. However, the use of aluminium in the construction of plant and equipment is limited.

Advantages : (1) High resistance to atmospheric conditions, industrial fumes, vapour and fresh or salt waters. Aluminium can be used with concentrated nitric acid (above 82 %) and acetic acid.

(2) Thermal conductivity of aluminium is 60 % that of pure copper.

Disadvantages:

(1) The mechanical strength decreases greatly above 150 °C.

(2) Aluminium cannot be used with strong caustic solution.

(3) Many mineral acids attack aluminium.

(4) Oxide and hydro-oxide films are formed rapidly, when its surface is exposed. Normally this film is thickened by chemical and electrolytic means. These provide so called anodised finishes.

Uses : A super grade is preferred for food and pharmaceutical use. It is used in many heat transfer applications. These are used as meat storage containers.

Aluminium alloys and modifications : A number of aluminium alloys are available with improved qualities and mechanical properties. Aluminium alloys are used in the construction of equipment producing medicinal substances, since aluminium does not affect the salts.

Aluminium is non-toxic to microorganisms. It has considerable use in biosynthetic processes such as the production of citric acid gluconic acid and streptomycin by deep culture methods. It is most useful for the construction of containers namely drums, barrels, rail tankers, etc.

Lead

Lead has the lowest cost and is used as collapsible tube material particularly for non-food products such as adhesives, inks, paints and lubricants. Lead tubes with internal linings are sometimes used for fluoride toothpaste. Lead chamber process is used in the manufacture of sulphuric acid.

Disadvantages : (1) Lead has low melting point and hence possesses poor structural qualities.

(2) It has high coefficient of expansion. Therefore, temperature strain results in permanent deformation.

In pharmaceutical practice, lead has little use, because of the risk of contamination even in traces produces toxicity and of cumulative nature. It is used for the construction of cold water pipes, waste pipes and dilution tanks for laboratories.

Lead alloys and modifications : Lead alloys with superior performance qualities have been established. For example, acid lead and copper lead are used in chemical industries. Some metals are added to lead for altering properties.

Silver and copper	improves corrosion resistance improves creep and fatigue resistance.
Antimony, tin, arsenic	hardens, still melting point is low.

Lead-lined steel structures are used for the construction of pipes, valves, vessels designed for operations at high temperatures, fluctuating temperatures or vacuum.

Copper and its Alloys

Copper is preferred when good thermal and electrical conductivity is required. It is relatively inexpensive and possesses fair mechanical strength. It can be fabricated easily into a wide variety of shapes. Copper is resistant to atmospheric moisture and oxygen, because a protective coating (copper oxide) is formed on the surface. Copper exhibits good corrosion resistance to strong alkalis, with the exception of ammonium hydroxide. It resists most organic solvents and aqueous solutions of organic acids. However, copper oxide is soluble in most acids and hence not a suitable material of construction, when it must contact any acid in the presence of oxygen or oxidizing agents.

Many components of formulation react with copper. Hence, copper is usually protected by a lining of tin, when used for in pharmaceutical plant. Copper is used for evaporators, pans (for sugar coating), stills and fractionating columns. However for the reasons of corrosion, it is largely replaced by stainless steel. Copper piping is used extensively for services such as cold water, gas, vacuum and low pressure steam.

Copper alloys, such as brass (copper-zinc alloy) and bronze (copper-tin alloy), can exhibit better corrosion resistance and better mechanical properties than pure copper.

- Brass is used for tube plates and condensers, for tubes and valves and in making nuts, bolts, rods, etc.
- Bronze is used for filter gauges, stirrers, pipes, autoclaves and special tablet punches and dies.

Most of the low-zinc alloys are resistant to hot dilute acids. High zinc alloys should not be used with acids and alkalis owing to the possibility of dezincification.

Tin

Tin has high resistance to a variety of substances and its salts are non-toxic. Tin is widely used in the food industry. Foods are packed in 'tin cans'. Steel sheet coated with tin is used for containers and condenser tubes. Similarly, brass and copper are also coated with tin.

Nickel and Its Alloys

Nickel-clad steel is used extensively for equipment in the production of caustic soda and alkalis. It is useful for such plants, as pans, vats, tanks, mixers, valves and pumps. Nickel exhibits high corrosion resistance and good mechanical strength. It has hardness as great as that of carbon steel. The metal can be fabricated easily. Oxidising conditions promote the corrosion of nickel, while reducing conditions retard it. Nickel is resistant to weak organic acids, such as citric acid, tartaric acid and stearic acid, which are used in the pharmaceutical preparations.

Monel alloy (67 % nickel and 30 % copper) is often used in food industry. In Inconel (77 % nickel and 15 % chromium), the chromium increases the resistance of nickel to oxidizing conditions.

Chromium

Chromium is used as plating. Chromium is not normally used even though it is hard and resistant to corrosion. It is mainly used in the manufacture of stainless steel, in combination with nickel.

Silver

Silver shows fair resistance to aqueous solutions of the halogen acids. Silver is generally used only in the form of linings because of its low mechanical strength and high costs. It is resistant to organic acids, but not to concentrated acids, such as hydrochloric acid, sulphuric acid and nitric acid. Silver has a higher thermal conductivity than all other metals. Silver is specially used in the manufacture of salicylates and acetic acid. A silver-plated basket is used for a hydroextractor utilized in vitamin crystallization. Solid silver vessel in a cast-iron jacket is used for bromination.

Platinum

Platinum is used when all other metals fail, because it is expensive. It is as strong as steel and is stable to hydrofluoric acids.

Comment 12-4. Why are noble metals not used for the construction of equipment?

NONMETALS—INORGANIC

Glass

A number of glass articles are used in daily life. Glass has the advantages of superior protective qualities, attractiveness and low cost. It is chemically inert to a large extent and available in a variety of sizes, shapes and colours. Glass containers practically offer excellent barrier against every element except light. UV rays and sunlight are harmful to certain ingredients and bring about chemical deterioration. Protective action against light can be achieved by amber-coloured glass. Protection against IR rays

can be obtained by using green glass. The disadvantages are its fragility and weight.

Glass is considered as a super-cooled liquid, though it is seen in solid state. The constituents are present in amorphous state. Glass is composed of the following constituents.

Sand	silica pure (silicon dioxide, SiO_2)	base material
Soda ash	sodium carbonate (Na_2CO_3)	improves the properties
Lime stone	calcium carbonate ($CaCO_3$)	improves the properties
Cullet	broken glass	fusion agent

Silicon dioxide is having a tetrahedron structure. The glass that is prepared by silicon dioxide alone is the most resistant, but relatively brittle. It can be melted and moulded at high temperatures. Therefore, cations such as sodium, potassium, calcium, magnesium, aluminium, boron, iron, etc. are added. These cations (available as oxides) modify the physicochemical properties of glass, so that it is suitable for the manufacture of glass with desired characteristics. However, this glass has low chemical resistance. Some varieties of glasses are given in Table 12-4.

TABLE 12-4
Some Varieties of Glasses

Type of glass	*Composition*	*Advantages or uses*
Soft glass (soda glass)	Sodium silicate Calcium silicate	Making glass bulbs and window glasses
Hard glass (potash glass)	Potassium silicate Calcium silicate	Glass apparatus, which resists the action of acids
Flint glass (Potash lead glass)	Potassium silicate Lead silicate	Optical instrument because of its refractive index
Jena glass	Zinc silicate Barium borosilicate	Laboratory glassware, because of its resistance to acids and alkali
Pyrex glass	Silicon dioxide Boron oxide Sodium oxide Small amounts of potassium, calcium, magnesium	Laboratory glassware and reactor vessels, because of its resistance to heat
Quartz glass	Pure silica	Silica crucibles, distilled water stills (for high purity), because of its low coefficient of expansion. It withstands temperature shock upto 1000 °C.

Glass containers used for pharmaceutical purposes are given in Table 12-5. These types are classified into four groups. These have varied degree of chemical resistance. The reasons for the low chemical resistance are as follows. Most of the alkali oxides such as Na_2O, K_2O, MgO and CaO enter the spaces within the structures and reduce the strength of inter-atomic forces between silicon and oxygen. The oxides decrease the melting point of glass and are comparatively free to migrate. This behaviour creates a number of problems in their use. These are:

(a) Oxides leach into the solution, raises the pH, hydrolyse or catalyse chemical reactions.

(b) Some times, glass flakes are formed in the solution.

However, boron oxide enters into the structural configuration of glass and does not leach out and hence is used in parenteral packings.

TABLE 12-5

Types of Glass used in Pharmaceutical Industry IP

Types	*General description*	*Properties*	*Uses*
I	Highly resistant Borosilicate (Alkali and earth cations are re placed by boron)	Resistant to alkali leaching, less brittle, low thermal expansion easy to clean and sterilise.	Containers for buffered and unbuffered, aqueous solutions and injectables.
II	Treated soda-lime glass	Surface alkali is neutralised by sulphur dioxide vapours. Glass surface is resistant to water.	Containers for buffered, aqueous solution with pH below 7.0, dry powders, oleogenous solutions.
III	Soda-lime glass	It releases comparatively more alkali. It offers moderate hydrolytic resistance.	Dry powders, oleogenous solutions.
IV	General purpose soda lime glass		Not for parenterals, used as containers for tablets, oral solutions, suspensions, ointments and liquids for external use.

Glassed Steel

Glassed steel is an inorganic product of fusion, which is cooled to a rigid condition without crystallising. It requires special considerations in its design and use. These surfaces are applied to heavy vessels. Normally, several coatings are fused in a furnace. Glassed steel combines the corrosion resistance of glass with the working strength of steel.

Advantages of glassed steel are:

(1) It has excellent resistance to all acids except hydrofluoric acid and hot concentrated sulphuric acid.

(2) It can be attacked by hot alkaline solution. Particularly suitable for piping when transparency is desirable.

(3) It is brittle and gets damaged by thermal shock. Hence it is protected using glass lined with epoxy polyester fibre glass.

(4) A nucleated crystallised ceramic metal composite form of glass has superior mechanical properties compared with conventional glassed steel.

(5) Glass linings are resistant to:
   (a) All concentrations of hydrochloric acids upto 120 °C.
   (b) Dilute concentrations of sulphuric acid up to the boiling point.
   (c) All concentrations of nitric acid upto boiling point.
   (d) Acid resistant glass with improved alkali resistance (up to pH 12).

Uses : Glass lined steel is used for handling of strong acids, alkalis and saline solutions. For small-scale manufacture and pilot plant work, glassed steel vessels are used.

Brick, Concrete and Clay

If corrosive conditions are severe and other high alloys fail, brick-lined construction is the only alternative. These bricks are made from carbon, acid-proof refractory materials. Phenolic resins, silicates and epoxy based materials are good against non-oxidizing acids, salts and solvents. Each type of cement has its own limitations. For example, sodium silicate based cement is good against acids up to 400 °C. Vitrified acid-resistant bricks are used for tanks, drains, culvets, etc. Granite is used in certain types of mills.

Concrete is an amorphous matrix of hardened cement paste in which the particles are reinforced. These have limited resistance to acids and bases and fail mechanically following absorption of crystal forming solutions (example is brine). It is used for tanks and special purpose structures.

Clay is used as a material of construction for settling basins and waste treatment evaporation ponds.

Porcelain and Stoneware

Porcelain enamels are used to coat steel, but enamels have slightly inferior chemical resistance. Stoneware avoids mechanical fragility of glass, but heat transfer is a problem. Acid-proof stoneware is highly resistant to acids, but has low strength. Porcelain and stoneware have the advantage of greater strength and resistant to acids and chemicals. These have poor thermal conductivity and hence can be damaged by thermal shock.

Ceramics are widely used on a small scale plants. Pipeline, tanks, vessels and filters are a few items of ceramics.

Enameled and Silicaware

Enameled ware may be used successfully only under moderate process temperatures and relatively mild conditions of mechanical and temperature shock. Glass coated on iron and steel is useful. Silica ware possesses the corrosion resistance.

Asbestos

Asbestos pads are used for sterile filtration, as it is fibrous and can be woven into cloth. It is a poor conductor of heat and hence used for heat insulation for pipe lining and for pipe jointing.

Comment 12-5. In what way, type II glass containers are different from remaining glass containers?

Comment 12-6. Nonmetals are preferred for the construction of equipment over metals. Explain.

NONMETALS—ORGANIC

Rubber

Rubber is used as such or as lining materials for the construction of plants. Both natural and synthetic rubbers are used.

Natural rubber : Rubber is a naturally occurring polymer, which is obtained as latex from rubber trees. It is a common example of an elastomer. *Elastomer* is a substance that can be stretched readily and when released, rapidly regains its original form.

Soft rubber : The naturally occurring polymer is known as *soft rubber*. It is a polymer of monomeric isoprene (C_5H_8). Thus, rubber is a polyisoprene with a formula $(C_5H_8)_n$. Soft rubber has the advantages of being resistant to dilute mineral acids, dilute alkalis and salts. The disadvantage is that soft rubber can be attacked by oxidising media, oils and organic solvents. Soft rubber is used as lining materials for plants, as it can bond easily to the steel.

Addition of carbon black to the soft rubber gives hardened rubber. It is used for making tyres, tubes and conveyor belts.

Hard rubber : When soft rubber is mixed with sulphur, warmed and set into a given shape, it retains its form. The sulphur combines with the polymeric chains of rubber and cross-links between them. This process is called *vulcanisation*. Soft rubber with 25 % or more sulphur is known as *hard rubber*. Hard rubber has the advantages of hardness and strength. So it is used for making gloves, bands, tubes and stoppers.

Rubber is a soft material, but can be hardened by adding carbon black. Hardened rubber is used for making tubes, tyres and conveyor belts.

TABLE 12-6
Some Varieties of Rubber

S.No.	Synthetic	Properties	Uses
1	Neoprene (polychloro prene)	• Does not burn readily like natural rubber. • Stable at high temperature.	Insulating material in electric cables, conveyor belts in coal mines, making hoses in the transportation of oils, rubber stoppers, cap-liners, dropper assemblies for eye drops etc.
2	Nitrile rubber	• Resistant to oil and solvents.	
3	Butyl rubber	• Resistant to - mineral acids & alkalis - concentrated acids (except nitric and sulphuric acid).	Used for closures of freeze dried product containers because of its low water vapour permeability.
4	Silicon rubber (poly-siloxanes)	• Resistant to - high & low temperatures, - attack to aliphatic solvents, oils and greases.	
5	Polyisoprene	• Stable at high temperature, translucent, flexibile.	

Synthetic rubber : Synthetic rubber has taken greater importance over natural rubber due to its superiority in properties such as resistance to oxidation, solvents, oils and other chemicals. Some synthetic rubber materials with their properties are reported in Table 12-6.

Synthetic rubber is thermoplastic, but when mixed with sulphur, warmed and set into a given shape, it retains its form. Vulcanisation of rubber is possible. It is used for making gloves, bands and tubes, caps for vials.

Plastics

Plastic materials have been in common use in various ways in our daily life. These are light in weight so that transportation is easy and cheap. These are available in a variety of shapes implying that it can be easily fabricated. Plastic containers are used for storing a number of substances such

as inorganic salts and weak mineral acid. In machines, plastic materials are preferred wherever moving parts are present indicating that it offers less friction. These have better resistance to environmental factors. In a similar manner, plastic materials also used in the construction of plants.

Plastics are synthetic resins containing long chains of atoms linked to form giant or macromolecules (polymers). They have high molecular weight (10^3 to 10^7).

Plastics have several **advantages**. These are:

(1) Low thermal and electrical resistance.
(2) Excellent resistance to weak mineral acids.
(3) Unaffected by inorganic salts.
(4) Resistance to slight changes in pH.

Plastics have **disadvantages** also. These are:

(1) Low mechanical strength.
(2) High expansion rates.

Basically, two types of plastics are used in pharmaceutical industry.

Thermosetting plastics : *Thermosetting plastics* can be formed under heat and pressure. But these cannot be softened or remoulded, once hardened. Some thermosetting plastics are made of phenolic and urea resins.

Thermoplastic plastics : *Thermoplastic plastics* are formed by the application of heat and pressure and can be softened and remoulded. This is a specific advantage. Scrap and rejected articles can be worked again to get new materials. Some thermoplastic materials and their uses are given below:

Polyethylene	cables, buckets, pipes
Polypropylene	milk cartons, ropes
Polyvinyl chloride	gloves, water proof garments
Teflon	gaskets, coatings

Based on the *utility* of plastics in plant construction, these can be categorised as:

1. Rigid materials
2. Flexible materials
3. Metallic surfaces
4. Plastic cements
5. Special case plastics

1. Rigid materials : These are phenolic resins with various inert fillers. These are used in the fabrication of a number of items. For example, Keebush is a rigid material (phenolic plastic) used for gears, bearing, etc. It is light in weight. Some of its applications are:

- Gears
- Bearing
- Vessels
- Pipes
- Fittings
- Valves
- Pumps
- Ducts
- Filter presses

Disadvantages : These are resistant to corrosion except oxidising substances and strong alkalis.

2. Flexible materials : These are thermoplastic materials. These materials can be rigid or flexible depending upon the amount of plasticizer added. These are used in the fabrication of:

- Tanks
- Pipes
- Ducts
- Funnels
- Buckets

3. Metallic surfaces : Plastics of polyethelene or polyvinyl chloride types are used along with plasticizers for the coating of metallic surfaces. These are used to protect the metal from corrosion. These linings are applied on:

- Tanks
- Vessels
- Stirrers
- Fans

4. Plastic cements : These are used for spaces between acid resistant tiles and bricks.

5. Special cases : Plastics are used as guards for moving parts of machinery. Nylon and PVC fibres are woven into filter cloths and are used for aseptic screening.

Wood

Wood is impregnated to resist acids or alkalis. Impregnated wood is not affected at high temperature. Wood is fairly inert chemically, but hydrolysed by the use of strong solutions, acids, alkalis, especially when these are hot. Wood is dehydrated and badly shrinks in concentrated solutions. Wood is used for tanks and vats. Its light weight is advantageous and occasionally used in filter presses, because metal filter press becomes heavy.

Comment 12-7. Why is hardening of rubber necessary?
Comment 12-8. What is the material used for the preparation of dropper assemblies of eye drops and why?
Comment 12-9. What is the desirable property for the stoppers used for freeze dried products?
Comment 12-10. Differentiate thermoplastics and thermosetting plastics.

Summary

A number of equipment are used in the manufacture of formulations, bulk drugs, antibiotics and biological products. These are made using several materials (metals or nonmetals) either individually or combined.

These are also used for making containers for processing as well as packing. These are fabricated using suitable materials. The knowledge on the properties of materials is essential for selecting a right kind of material for construction. The successful utilization of equipment depends on the design of equipment, selection of material and techniques of fabrication. Thus the understanding the properties of materials is of interest.

Several factors influence the selection of materials. Chemical factors involve the interaction of chemicals (present in the equipment) and ingredients (present in the formulation). The net result is the contamination of product or destroying the functionality of the equipment. The physical factors are: strength of metal, weight of the equipment, wear properties, thermal conductivity, thermal expansion, ease of fabrication, cleansing, transparency, etc. The economic factors include the initial costs and the maintenance costs. Sterilization of equipment is essential in the production of parenterals, opththalmic products, antibiotics and biological products. Normally stainless steel is used for the purpose. Smooth and polished surfaces of the equipment allow the easy cleaning. Stainless steel and glass are suitable materials. The fabrication of an equipment involves several steps through which the materials gets transformed. Normal glass and plastics allow easy fabrication. Wherever heat transfer is required, thermal conductivity become relevant and iron, glass and graphite tubes are used in the fabrication of heat exchanger.

Among the number of materials available for selection, ferrous metals are widely preferred for the construction of plants. Cast iron, steel carbon and stainless steel are a few variants. Even in stainless steel, several variants are available such as martensitic, ferritic and autenitic. Thus several alloys are prepared by suitably combining with other metals to achieve the desired characteristics. Thus stainless steel is abundantly used on account of easy fabrication and corrosion resistance. Several non-ferrous metals are also used for the construction of equipment. Aluminum has several advantages, but limited use in fabrication of equipment.

Lead is used for preparing collapsible tubes for non-food products. In pharmaceutical practice, lead has little use, because of risk of contamination, which even in traces produces toxicity. Copper and its alloys have good thermal, electrical conductivity and used for evaporator pans, sugar coating pans, stills and fractionating columns. Copper is used for the manufacture of valves, tube plates of heat exchangers, condensers, etc. Nickel and its alloys are used extensively for equipment (pans, vats, tanks, mixers, valves and pumps) in the production of caustic soda and alkalis.

Nonmetals such as glass, rubber and plastics also find their applications, not as process equipment, but as containers, closures and other medical accessories. Several varieties of glasses are available, each having

specific applications. The pharmacopoeia recommends four types of glasses with specific properties and applications. Glass-lined steel is used for handling of strong acids, alkali and saline solutions. Both natural and synthetic rubbers are used as insulating materials in electric cables, conveyor belts, rubber stoppers, cap-liners, dropper-assembly, gloves, bands, etc. Plastics have low thermal and electrical resistance, unaffected by inorganic salts and slightly resistance to acids. Polymers are diverse compounds with varied properties ranging from rigid to flexible. These are used as linings on the metal surface to protect the metal from corrosion.

QUESTION BANK

Each question carries one mark

Note : Encircle the alphabet which corresponds to the single best response.

1. Water attack test is performed on glass in order to find the limits of one of the following.
   A. Acid liberated B. Alkali liberated
   C. Conductivity D. Metal ions
2. In pharmaceutical packing, collapsible tubes made from lead are not used as such, for one of the following reasons.
   A. Costly metal B. Difficulty in packing
   C. Risk of poisoning D. Soft in strength
3. Air-tight sealed containers are used for one of the following reasons.
   A. Capsules B. Injections
   C. Liquid preparations D. Tablets
4. One of the following glass containers is used for the storage of light sensitive pharmaceuticals.
   A. Air-tight B. Amber coloured
   C. Unit dose D. Well closed
5. Containers meant for storage of injections (buffered and un-buffered aqueous solutions) are made from one of the following type of glasses.
   A. Borosilicate B. General purpose
   C. Lime soda D. Neutral
6. Hermetic sealed containers are also known as:
   A. Air-tight containers B. Multi-dose containers
   C. Single-dose containers D. Well-closed containers
7. Which one of the following materials is used for the construction of outer surface of jacket of steam pans, because of its low thermal conductivity?
   A. Carbon steel B. Cast iron
   C. Copper D. Stainless steel

8. Which metal makes the steel corrosion resistant?
   A. Chromium and nickel
   B. Copper and selenium
   C. Tantalum and molybdenum
   D. Titanium and niobium
9. One of the containers is currently used for bulk packaging of tablets, capsules, powders and food materials.
   A. Card board
   B. Glass
   C. Metal
   D. Plastic
10. Which metals improve creep and fatigue resistance properties of lead?
    A. Chromium
    B. Copper
    C. Silicon
    D. Tin
11. Protection against IR rays can be achieved using one of the following glass containers.
    A. Amber coloured
    B. Green coloured
    C. Transparent
    D. Yellow coloured
12. Rubber contains one of the following chemical units?
    A. Amino acid
    B. Glycosidal
    C. Isoprene
    D. Sugar
13. Vulcanisation of rubber involves the addition of one of the following substances to the soft rubber.
    A. Magnesium
    B. Phosphorus
    C. Potassium
    D. Sulphur
14. Phenolic plastics are one of the following types
    A. Cement
    B. Flexible
    C. Metallic
    D. Rigid
15. Which glass is used for the preparation of optical instruments because of its refractive index?
    A. Flint glass
    B. Hard glass
    C. Pyrex glass
    D. Soft glass
16. Which type of glass is used for the preparation of distilled water stills?
    A. Hard glass
    B. Jena glass
    C. Quartz glass
    D. Soft glass
17. Which type of rubber is used for making of gloves, bands, tubes, caps and stoppers?
    A. Hard rubber
    B. Neutral rubber
    C. Soft rubber
    D. Vulcanised rubber
18. Which thermoplastic material is used for fabrication of tanks and pipes?
    A. Flexible materials
    B. Metallic surface
    C. Plastic cement
    D. Rigid materials

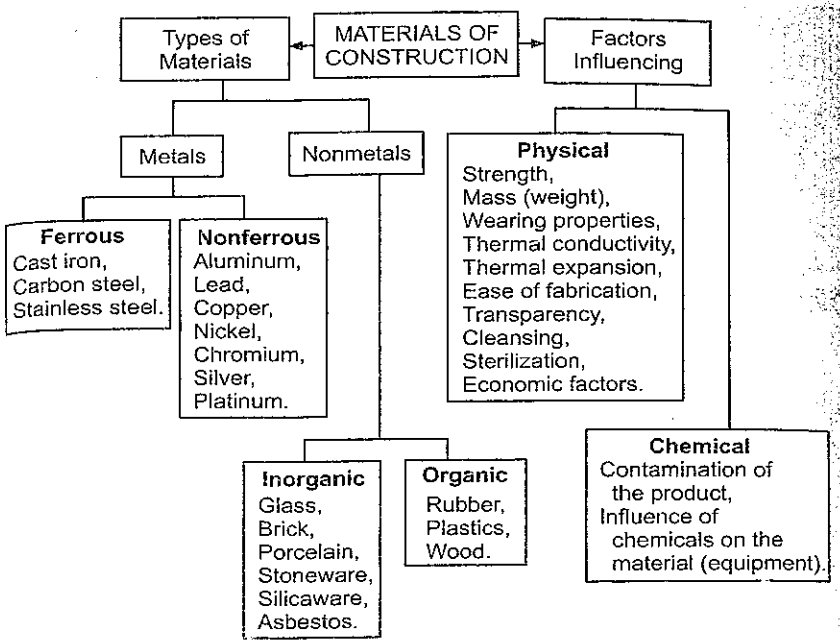
19. Which type of rubber is used as lining material that can bond easily to the steel, in the plant construction?
    A. Butyl rubber
    B. Carbon rubber
    C. Hard rubber
    D. Soft rubber
20. Which one of the following is NOT applicable to plastics?
    A. High mechanical strength
    B. Low thermal and electrical resistance
    C. Resistance to slight changes in pH
    D. Resistance to weak mineral acids

Each question carries 2 marks

1. Write the usefulness of glass lined equipment in the pharmaceutical plant.
2. List important types of glass containers. Mention an example of formulation that is stored in each type of container.
3. Arrange the following materials of construction in descending order of their reactivity: copper, iron, zinc, aluminum, magnesium, tin and lead.
4. Explain the following: pop star can make all zebras in town like his cars.
5. Plastic containers are used to store aerosol. True or false. Justify.

Each question carries 5 marks

1. Explain the importance of stainless steel in pharmaceutical industry.
2. Write a note on the utility of glass and stainless steel in pharmaceutical industry.
3. Describe steel as a material of plant construction.
4. Name five important classes of plastics. Mention their applications in pharmaceutical industry.
5. Describe the steel alloys used in pharmacy practice.
6. What are the properties of glass? What are its applications as a material of construction?
7. Describe various types of iron as materials of construction.



MIND MAP OF MATERIALS OF CONSTRUCTION

CHAPTER 13

Corrosion

Theories of Corrosion
Factors Influencing Corrosion
Types of Corrosion
Prevention and Control of Corrosion

LEARNING OBJECTIVES

After reading this chapter, the reader should be able to:

- Explore the basic nature of corrosion, the theories involved and their relevance in pharmaceutical industry.
- Review some basic environmental-, process- and material- related factors influencing the corrosion.
- Describe the types of corrosion processes, giving importance for identifying the causes, reactions and the nature of damage.
- Suggest the measures to prevent and control the corrosion damage of equipment.

Corrosion is defined as the reaction of a metallic material with its environment, which causes a measurable change to the material and can result in a functional failure of the metallic component or of a complete system.

Metals spontaneously undergo gradual destruction when exposed to the atmosphere. In chemical terminology, such destruction is known as corrosion. The familiar example of corrosion is the rusting of iron, due to atmospheric conditions (air or oxygen). In this, a layer of reddish scale and powder of oxide (Fe_3O_4) is formed, and the iron becomes weak. Other gases are halogen, sulphur dioxide and hydrogen sulphide. Exposure of the surface to air, water and caustic chemicals are responsible for corrosion. Since metals are good conductors, they undergo electrochemical changes on their surfaces. The compound that is formed during corrosion is referred to as *corrosion product* and the metal surface is said to be *corroded.* The *corrosion media* are generally liquids (mostly aqueous solutions), but also solids and gases.

The process of corrosion is slow and occurs only on the surface of the metals. The surface changes due to corrosion are carried through the equipment and destroy the performance and fabrication in due course. Some times, the leached metal may contaminate the product. The material of construction must be resistant to corrosion and erosion. Hence, adequate attention should be paid while selecting the materials for construction of equipment.

Corrosion can be either dry or wet type.

Dry corrosion or Chemical corrosion : It involves the direct attack of dry gases (air and oxygen) on the metals through chemical reactions. As a result an oxide layer is formed over the surface. This oxide scale forms a barrier that tends to restrict further oxidation. On further oxidation, the metal rapidly diffuses outwardly and the gas diffuses inwardly. Thus, the total metal gets destroyed. Aluminium forms a non-porous, very thin and tightly adhering protective oxide film (Al_2O_3) on its surface. This film does not permit corrosion to occur. Magnesium also forms a stable but porous oxide film, thereby more oxygen can diffuse through the film. So its corrosion continues. This type of corrosion is not common.

Wet corrosion or Electrochemical corrosion : It involves the direct attack of aqueous media (strong or dilute, acidic or alkaline) on metal through electrochemical reactions. The moisture and oxygen are also responsible. In this type, two dissimilar metals or alloys are immersed in a solution. The metals form cathodic and anodic areas between which current flows through the conducting solution. Corrosion always occurs at anodic area. This type of corrosion is quite common.

Applications

Knowledge of corrosion is helpful in certain areas to prevent problems.

Dies and punches : In the compression of tablets, dies and punches should be free from rust and corrosion. Chromium plated dies and punches are used, so that the problems such as pits and abrasion can be avoided.

Milling equipment : In these equipment, a perfect fit between the moving parts should be maintained for effective size reduction. Though corrosion does not effect the performance of the mill or product, surface imperfections do not facilitate proper cleaning of the equipment. Hence, the associated problems persist.

Chemical processing reactors : Diverse nature of solutions which come in contact with the reactor surface often lead to corrosion on account of corrosive media and environmental conditions.

Fermenters : Glass, glass-lined and stainless steel (SS) materials are used for the construction of the fermenters. During fermentation, the release of trace metals from the equipment may have deleterious effects on the enzyme system and metabolic pathways of the organisms. The possible corrosion aspects in fermenters are pits and crevices, which make it difficult to clean and remove the contamination. Most of the operations are conducted at normal temperatures and the pH of the media would be around neutral. Maintenance of hygiene, need for sterility and prevention of contamination are important considerations in the construction of fermenters.

Storage containers : Prolonged storage of reactive chemicals leads to corrosion of the containers.

This chapter highlights the general aspects of corrosion such as corrosive environments, principles, types of corrosion and measures to prevent corrosion.

THEORIES OF CORROSION

The metal surface undergoes an electrochemical reaction with the moisture and oxygen in the atmosphere. This theory is known as *electrochemical theory of corrosion*. The mechanism involves the formation of a galvanic cell (anodic and cathodic areas), by different metals (e.g. Fe and Cu) or in different areas on the same piece of metal (e.g. iron).

When galvanic cells are formed on different metals, the corrosion is known as *galvanic corrosion*. These reactions are illustrated using the metals in the presence of eletrolyte solution such as hydrochloric acid.

Corrosion Reactions on Single Metal

Electrochemical reactions are illustrated by considering the corrosion on a piece of iron in hydrochloric acid. Anodic and cathodic areas are formed on the surface of iron, owing to surface imperfections (localised stresses, grain orientation, inclusions in the metals) or due to variations in the environment. Numerous tiny reactions may occur (Figure 13-1).

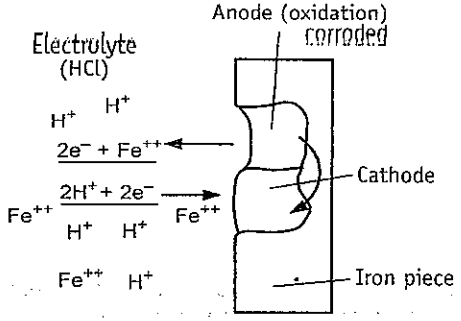


Figure 13-1. Electrochemical mechanism of corrosion. Different areas on the iron piece are illustrated.

Reaction at anode : Oxidation takes place with the release of electrons. Positively charged iron atoms get detached from the solid surface and enter into solution (electrolyte) as positive ions.

At anode: $Fe \longrightarrow Fe^{++} + 2e^-$ (indicated by rough surface)
(oxidation)

The released free electrons (negative charge) pass round the external circuit.

Reaction at cathode : Reduction of constituents occurs with the taking up of electrons. The free electrons reach the cathode and react with some positively charged species such as hydrogen ions in the electrolyte solution. In the absence of acid, water itself dissociates to generate H^+ ions.

At anode: $2H^+ + 2e^- \longrightarrow H_2\uparrow$ (indicated by formation of bubbles at the surface)
(oxidation)

The amount of metal (iron) which is dissolved in the electrolyte is proportional to the number of electrons flowing, which in turn depends upon the potential and resistance of the metal.

The overall reaction:

$$Fe + 2H_2O \longrightarrow \underset{\text{Red brown rust}}{Fe(OH)_2} + H_2\uparrow$$

High evolution of H_2 accompanies rapid corrosion such as hydrogen embrittlement. In the electrochemical series, all metals above hydrogen have a tendency to get dissolved in acidic solution with simultaneous evolution of oxygen. Depletion of hydrogen also enhances corrosion. In moderate concentrations of H_2, corrosion slows down.

Corrosion Reactions Between Metals

Galvanic corrosion results from the flow of current from a more active metal (anode) to a less active metal (cathode). A few examples are: steel pipe connected to copper plumbing and lead-antimony solder around the copper wire.

For example, zinc dissolves and forms an anode, while copper (Cu) forms the cathode. These two metals form two electrodes and their presence in an electrolytic solution forms a galvanic cell (Figure 13-2).

Spontaneous reaction can occur when two electrodes are connected through an external wire. Reactions at anode and cathode are:

At anode: $Zn \longrightarrow Zn^{++} + 2e^-$ (indicated by rough surface)
(oxidation)

At anode: $2H^+ + 2e^- \longrightarrow H_2\uparrow$ (indicated by formation of bubbles at the surface)
(reduction)

The corrosion current flows at the expense of the anode metal, which gets corroded continuously, whereas the cathode metal is protected.

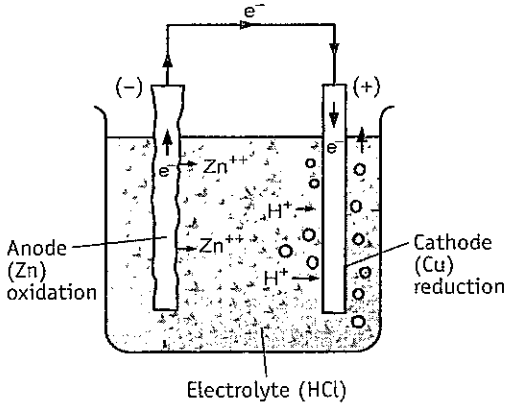


Figure 13-2. Galvanic mechanism of corrosion. Reactions between different kinds of metals.

In some cases, evolution of the hydrogen gas is slow. The accumulation of a layer of hydrogen on the cathode surface slows down the corrosion. This is called *cathodic polarisation*. It forms an insulating layer that slows down or stops the electrochemical reaction.

Corrosion Involving Oxygen

The oxygen dissolved in an electrolyte can react with accumulated hydrogen to form water. Depletion of hydrogen layer allows corrosion to proceed.

At cathode: $O_2 + 2H_2 \longrightarrow 2H_2O$ (indicated by formation of bubbles at the surface)

The above reaction takes place in acid medium. Example is rusting of iron. The surface of iron is usually coated with a thin layer of iron oxide. However, if this iron oxide film develops crack, anodic and cathodic areas are created. When the corrosion medium is alkaline or neutral, oxygen is absorbed. The presence of moisture (or water) promotes corrosion. The effective concentration of oxygen in water adjacent to cathode depends upon the degree of aeration, temperature and presence of dissolved salts.

Comment 13-1. What is the relationship between corrosion and metals in electrochemical series?

Comment 13-2. For corrosion to occur, at least two different metal surfaces are required. True of false. Explain.

Comment 13-3. In a solution, two dissimilar metals should not be allowed to come in contact with each other. Why?

FACTORS INFLUENCING CORROSION

A number of processing factors affect the rate of corrosion. Material related factors are considered while procuring the equipment.

Material Related Factors

The nature of metal is an important factor that influences the corrosion. Some of these aspects are described, while explaining the theories of corrosion. Purity of material and its physical state, namely grain size, orientation of crystals, stress, etc. influence the corrosion. On the other hand, higher volatility and solubility of corrosion products enhance the extent of corrosion.

Solution pH

Generally acidic media induce more corrosion than alkaline or neutral media. The pH affects the rate of corrosion of metals by one of the three general patterns.

(1) Metals such as iron dissolve rapidly in acidic solution. In the middle pH range (4 to 10), the concentration of H^+ ions is low. Hence, the corrosion rate is controlled by the rate of transport of oxidizer (oxygen).

(2) Certain amphoteric metals dissolve rapidly in either acidic or basic solutions. E.g. aluminium and zinc. Corrosion proceeds.

(3) Noble metals are not affected by pH. E.g. gold and platinum.

The H^+ ions have a tendency to capture electrons to form H_2 gas and promote anodic corrosion.

Oxidising Agents

Oxidising agents may accelerate the corrosion of one class of materials, whereas retard another class. Oxidizing agents such as oxygen (O_2) react with hydrogen to form water. Once hydrogen is removed, corrosion is accelerated. For example, copper in sodium chloride solution follows this mechanism.

Oxidising agents retard corrosion due to formation of surface oxide films, which makes the surface more resistant to chemical attack. Therefore, adsorbed oxygen layer is essential. Thus a balance between the power of oxidising compounds to preserve the protective film and their tendency to destroy the protective film determine the corrosion of the metal. For example, an oxide film is rapidly formed on stainless steel. This film cannot be dissolved or destroyed easily even in severe operating conditions. However, sulphuric acid and hydrochloric acid can easily destroy this oxide film.

Temperature

The rate of corrosion tends to increase with rising temperature. It has a secondary effect. The influence of temperature on corrosion may follow several of these mechanisms.

(1) Increase in temperature reduces the solubility of oxygen or air. The released oxygen enhances the corrosion.

(2) Increase in temperature induces phase changes, which enhances the rate of corrosion. At high temperatures, organic chemicals are saturated with water. As the temperature decreases, water gets condensed.

(3) Oxygen is needed for maintaining iron oxide film, which prevents corrosion. In the absence of oxygen (due to increase in temperature), the corrosion of stainless steel increases.

(4) Copper-based alloys do not depend on the oxide film for corrosion.

The reaction is diffusion-rate controlled, which increases with increasing temperature.

Velocity

When the corrosive medium moves at a high velocity along the metallic surface, the rate of corrosion frequently increases. The mechanism is diffusion-rate controlled. High velocity has the following effects.

(1) Corrosion products are formed rapidly, because chemicals (including oxidising substances) are brought to the corroding surface at a higher rate.

(2) The accumulation of insoluble film on the metallic surface is prevented. Therefore, corrosion resistance of these films decreases.

(3) The corrosion products (or film) are easily stifled and carried away, thereby exposing the new surfaces for corrosion.

Thus corrosion proceeds unhindered. This factor is responsible for the corrosion of a number of equipment parts, such as condensers, evaporator pipes (in the vicinity of bends in the pipes), propellers, agitators and centrifugal pumps. Corrosion occurs frequently in small diameter tubes/pipes through which corrosive liquid may be circulated at high speeds as shown in the above examples.

Surface Films

Once corrosion is started, its further progress is often controlled by the nature of surface films. A variety of surface films have been observed. Thin oxide films are formed on the surface of stainless steel (rusting). These films tend to retain or absorb moisture, which delays the time of drying. Hence, the surface exposure to atmosphere or corrosive vapour increases

the extent of corrosion. The rust films formed on low alloy steels are more protective than those formed on unalloyed steel.

Insoluble salts such as carbonates and sulphates may be precipitated from hot solutions on the metal surfaces. These protect the metal surfaces. If the film is porous (e.g. zinc oxide), corrosion continues. Nonporous films (e.g. chromium oxide film on iron) prevent further corrosion.

Oil and grease films may form on the surfaces either intentionally or naturally. These films protect the surface from direct contact with corrosive substances. E.g. metals submerged in sewage or equipment used for processing oily substances.

Constituents of the Reaction Media

A number of other processing factors such as constituents of the reaction media also influence the rate of corrosion.

- The presence of impurities, for example, sodium and other chlorides, leads to increased conductivity of the liquid layer in contact with the metal surface, thereby corrosion is speeded up. Impurities in the metal generally cause heterogeneity and form minute electrochemical cells (anodic and cathodic parts) at the exposed parts. Then anodic parts get easily corroded.
- The presence of anions like silicates in the medium leads to the formation of insoluble reaction products, which inhibit further corrosion. On the other hand, chlorides destroy the protective and passive surface film, thereby exposing the metal/alloy surface for fresh corrosion.

Humidity of air is the deciding factor which is critical. The value of critical humidity depends on the physical characteristics of the metal as well as the nature of corrosion products.

Other Factors

The concentration of corrosive chemicals in the environment influences the rate of corrosion. In equipment such as distillation columns, reactors and evaporators, the concentration can change continuously, making prediction of corrosion rate difficult. In addition, corrosion rates are seldom linear over a wide range. Concentration is important during plant shut-down. The presence of moisture that collects during cooling can turn innocuous chemicals into dangerous corrosives.

Comment 13-4. Rusting of iron is quicker in saline water than in ordinary water. Why?

Comment 13-5. Corrosion is often more rapid at the places where some corrosion is already taken place. Why?

Comment 13-6. Aluminum corrodes faster than iron, even though iron is placed below aluminum in the electrochemical series. Why?

Comment 13-7. Why is corrosion high in acidic medium than alkaline medium?

TYPES OF CORROSION

Pure metals and their alloys tend to enter into chemical union with the components of a corrosive medium to form stable compounds. Corrosion can be broadly classified as follows.

1. Fluid corrosion, General
2. Fluid corrosion, Localised
3. Fluid corrosion, Structural
4. Fluid corrosion, Biological

Fluid Corrosion : General

When corrosion is generally confined to a metal surface, it is known as *general corrosion*. This type occurs in a uniform fashion over the entire exposed surface area at a wide range of temperatures. General corrosion is of two types.

Physicochemical corrosion : The effects of this type are swelling, crazing, cracking, softening, etc. Examples are plastics and nonmetallic material.

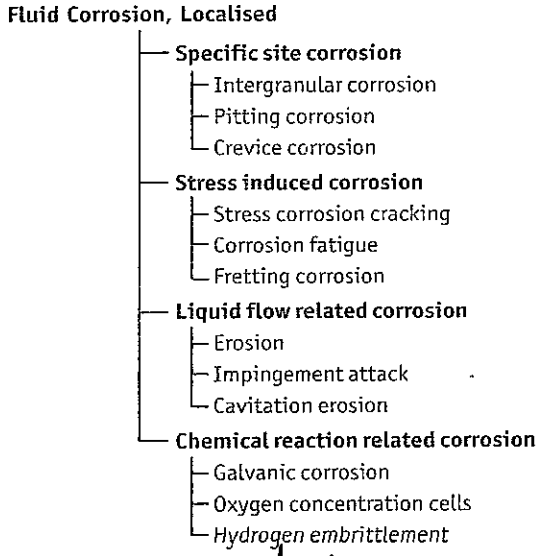


Figure 13-3. Classification of localised fluid corrosion.

Electrochemical corrosion : This type of corrosion occurs at discrete points of metallic surfaces when electricity flows from cathodic area to

anodic area. Metallic surface gets divided into anodic portion or cathodic portion.

Fluid Corrosion : Localised

Fluid corrosion is the most frequently observed on different locations in a material. It occurs in numerous ways. It is further classified as given in Figure 13-3.

Specific site corrosion : Mechanically weak spots or dead spots in a reaction vessel cause specific site corrosion.

Inter-granular corrosion : Selective corrosion that occurs in the grain boundaries in a metal/alloy is called as intergranular corrosion. In this type of corrosion, the grain boundaries contain material, which shows electrode potential more anodic than that of the grain centre in the particular corroding medium. This may be due to the precipitation of certain compounds at the grain boundaries, thereby leaving the solid metal solution (just adjacent to that grain boundary) impoverised (or depleted or poor) on one constituent. The impoverised solid solution is anodic with respect to the grain centers and the precipitated compound, so that it will be attacked preferentially by the corrosive environment (Figure 13-4).

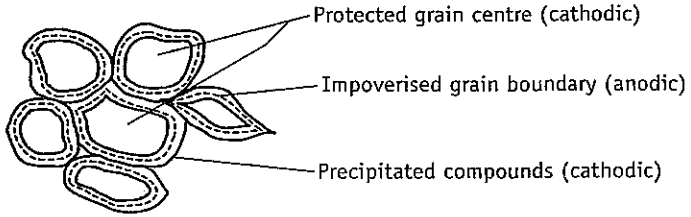


Figure 13-4. General inter-granular corrosion.

Microscopic examination can reveal clearly the intergranular corrosion. When severe, this attack causes a loss of strength and ductility out of proportion to the amount of metal actually destroyed by corrosion. Crystalline grain structure as such is not attacked appreciably. One example is:

$$\text{Austenitic stainless steel} + \text{Nitric acid} \xrightarrow{\text{hot condition}} \text{Grain boundary precipitation}$$

Stainless steel is stabilized by incorporation of niobium/titanium or carbon (less than 0.03 %).

Pitting corrosion : This type of corrosion results in development of pits and cavities. They range from deep cavities of small diameter to shallow depressions. Example is:

$$\text{Alloy of aluminium or stainless steel} + \text{Aqueous solution} \xrightarrow{\text{chlorides}} \text{Cavities}$$

Pitting of a metal occurs when there is a break in the protective oxide layer and imperfections on the underlying metal. This gives rise to the formation of small anodic and large cathodic areas. The presence of the extraneous impurities (e.g. sand, dust and scale) embedded on the surfaces of metals are also responsible for pitting. Owing to the differential amount of oxygen in contact with the metal (Figure 13-5), the small part (underneath the impurity) becomes the anodic area and the surrounding large part becomes the cathodic area. Once a small pit is formed, the rate of corrosion will be increased. Inhibitors are sometimes helpful in preventing pitting corrosion.

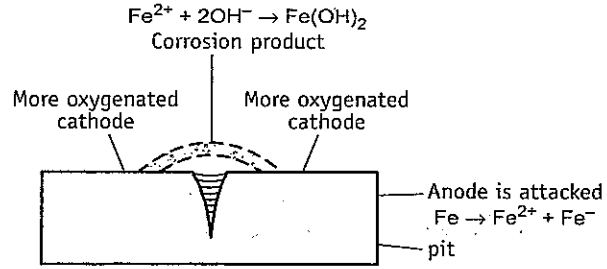


Figure 13-5. Pitting corrosion at the surface of iron.

Crevice corrosion : In this type, corrosion occurs in crevices because solutions are retained at such places, which takes longer time to dry out. When this occurs, the intensity of attack is usually more severe than surrounding areas of the same surface. Crevices are formed because of the metal contact with another piece of the same or other metal or with a non-metallic material. Corrosion in the crevices is due to a number of reasons as given below:

- Deficiency of oxygen
- Acidity changes
- Buildup of ions
- Depletion of inhibitor

Stress induced corrosion : Residual internal stress in the metal or external applied stress accelerates the corrosion. Residual internal stress is produced by:

- Deformation during fabrication.
- Unequal rate of cooling from high temperatures.
- Internal stress rearrangements involving volume changes.
- Stress induced by rivets, bolts and shrink fits.

Stress corrosion occurs along narrow paths, forming anodic areas with respect to the more cathodic areas at the metallic surface (Figure 13-6).

Presence of stress produces strains, which result in localized zones of higher electrode potentials. These become so chemically active that these are attacked, even by a mild corrosive environment.

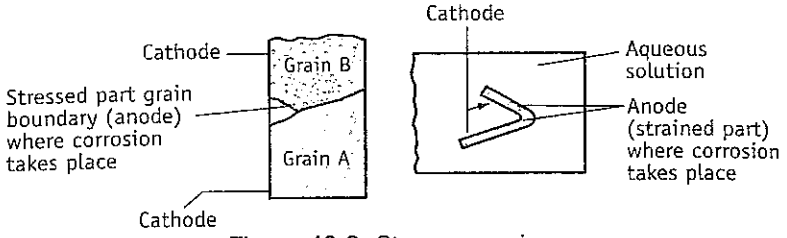


Figure 13-6. Stress corrosion.

Eliminating high stress areas prevents this type of corrosion. The external stress can be kept at minimum by employing suitable experimental conditions.

Stress corrosion cracking : At the surface, if the tensile stress is equal to or more than the yield stress, the surface develops cracks. This is known as *stress corrosion cracking*. Examples are:

- Cold-formed brass develops crack in the environment of ammonia.
- Embrittlement cracking of steel is observed in caustic solution.

Corrosion fatigue : Corrosion fatigue is the ability of a metal surface to withstand repeated cycles of corrosion. The metal surface is stressed and simultaneously attacked by the corrosive media. Pits (concentration points) indicating corrosion are formed initially, which further develop into cracks. As this process continues, the surface looses its fatigue resistance and ultimate failure of equipment.

The protective surface oxide film reduces corrosion. Under cyclic or repeated stress conditions, rupture of protective oxide films takes place at a higher rate than at which new protective films can be formed. Therefore, the rate of corrosion is enhanced.

Fretting corrosion : Fretting corrosion occurs when metals slide over each other and cause mechanical damage to one or both. During relative movement of metals, two processes may occur, (*i*) frictional heat is generated, which oxidizes the metal to form oxide films (*ii*) removal of the protective films resulting in exposure of fresh surface to corrosion attack.

This can be avoided by using harder materials, minimising friction by lubrication or by proper designing of the equipment, so that no relative movement of parts takes place.

Flow related corrosion : Liquid metals can cause corrosion. Usually the driving force is the tendency of the liquid to dissolve solids or penetrating the metal along the grain boundaries at places of wetting. Corrosion rate is enhanced at high temperatures. A few examples are:

- Mercury attack on aluminium alloys.
- Molten zinc on stainless steel.

Impingement corrosion : This is also referred to as erosion-corrosion or velocity accelerated corrosion. It is accelerated by removal of corrosive products (such as oxide films), which would otherwise tend to stifle the corrosion reaction.

Erosion : Erosion is the destruction of a metal by abrasion and attrition caused by the flow of liquid/gas (with or without suspended solids). The additional factors that can influence erosion include:

- Alloy contents of the steel (e.g. chromium, copper, manganese).
- Pipe system design and component geometry.
- Water and steam composition (especially pH and oxygen content).

The use of harder metals and changes in velocity or environment are used to prevent erosion.

Cavitation erosion : Formation of transient voids or vacuum bubbles in a liquid stream passing over a surface is known as cavitation. The bubbles may collapse on the metal surface thereby causing severe impact or explosive effect. Therefore, considerable damage and corrosion is observed. The protective films also get destroyed due to impact.

Cavitation erosion is observed around propellers, rudders in pumps, etc. Redesign, use of a more resistant metal and protective coatings are required to avoid this type of corrosion.

Chemical reaction related corrosion : Corrosion involves chemical reactions such as oxidation and reduction at anode and cathode, respectively.

Galvanic corrosion : Galvanic corrosion is associated with the flow of current to a less-active metal (copper cathode) from a more-active metal (zinc anode) in the same environment. Coupling of two metals, which are widely separated in the electrochemical series, generally produces an accelerated attack on the more active metal, zinc, i.e. anodic corrosion. Therefore, a combination of metals which are as close as possible in the electrochemical series should be chosen.

In galvanic corrosion, the effect of area is very important. For example, steel rivets on copper (Cu) plates will corrode much more rapidly than a steel plate with copper rivets. Corrosion at the anode may be 100 to 1000 times higher, if the two areas are same.

Protective oxide films tend to reduce galvanic corrosion. Insulating materials can be placed between two metal faces to prevent corrosion. For example, plates when bolted together, specially designed plastic washers can be used.

Oxygen concentration cell : This type of corrosion is due to the presence of oxygen electrolytic cell, i.e. a difference in the amount of oxygen in solution at one point exists when compared to another. Corrosion is accelerated where oxygen concentration is least, for example, under gaskets, stuffing boxes, etc. because formation of an oxide film is not possible. This also occurs under solid substances that may be deposited on a metal surface as ready access to oxygen is shielded. Redesign/change in mechanical conditions must be used to overcome this situation.

Hydrogen embrittlement : Hydrogen can penetrate carbon steel and reacts with carbon to form methane. The removal of carbon results in decreased strength. Corrosion is possible at elevated temperatures as significant hydrogen partial pressure is generated. This causes a loss of ductility, (hydrogen embrittlement) and failure by cracking or blistering of the steel. Resistance to this type of attack is improved by alloying with chromium/molybdenum.

Hydrogen damage can also result from hydrogen generated by electrochemical corrosion reaction. The atomic hydrogen formed on the metal surface diffuses into the metal and forms molecular hydrogen at micro-voids. The result is failure by embrittlement, cracking and blistering. This phenomenon is observed in solution of specific weak acids such as hydrogen sulphide and hydrocyanic acid.

Fluid Corrosion : Structural

In structural fluid corrosion type, the structural (mechanical) strength is reduced on account of corrosion. This may occur when one component of the alloy is removed or released into the solution. The corrosion products may remain in the plant. Two examples are presented here.

Graphite corrosion : Graphite is an allotropy of carbon. Graphite corrosion occurs in gray cast iron. The metallic iron is converted into corrosive products leaving a residue of intact graphite mixed with iron corrosive products and other insoluble constituents of cast iron. When the layer of graphite and corrosive products is impervious, corrosion will cease or slow down. If the layer is porous, the corrosion will progress by galvanic behaviour between graphite and iron.

When carbon steel is heated for prolonged periods at temperatures higher than 455 °C, carbon may get segregated, which is then transformed into graphite. Hence, the structural strength of steel is affected. Employing killed steel or low alloyed steels of chromium and molybdenum or chromium and nickel can prevent this type of corrosion.

Dezincification : This type of corrosion is seen in brass that contains more than 15 % zinc. In brass, the principal product of corrosion is metallic copper, which may redeposit on the plant. Another mechanism involves the formation of zinc corrosion products leaving the copper residue.

Corrosion may occur as plug filling pits (plug type) or as continuous layers surrounding the unaffected core of brass (general type). It can be reduced by the addition of small amount of arsenic, antimony or phosphorus to the alloy.

Fluid Corrosion : Biological

The metabolic action of microorganisms can either directly or indirectly cause deterioration of a metal. Such a process is called biological corrosion. Microorganisms associated with corrosion are either aerobic or anaerobic. The causes for biological corrosion are:

(1) Producing corrosive environment or altering environmental composition.
(2) Creating electrolyte-concentration cells on the metal surface.
(3) Altering resistance to surface films.
(4) Influencing the rate of anodic/cathodic reaction.

Sporovobrio desulphuricous organism is responsible for the anaerobic corrosion of iron and steel. The sequence of reactions associated with anaerobic sulphate reducing bacteria is as follows.

Anodic solution of iron:

$$8H_2O \rightleftharpoons 8H^+ + 8\,(OH)^-$$

$$4Fe + 8\,H^+ \rightleftharpoons 4Fe^{2+} + 8\,H$$

Depolarization, due to activity of bacteria:

$$H_2SO_4 + 8\,H \rightleftharpoons H_2S + 4\,H_2O$$

Corrosion products:

$$Fe^{2+} + H_2S \rightleftharpoons FeS + 2\,H^+$$

$$3Fe^{2+} + 6\,(OH)^- \rightleftharpoons 3Fe(OH)_2$$

The principal corrosion products are black iron sulphide and ferrous hydroxide. The corrosion is intense and localized.

The role of biological corrosion may be explained using anaerobic sulphate reducing bacteria in slightly acidic or alkaline soils. The optimum conditions for their growth are 25 to 30 °C and the pH is from 5 to 9 (Figure 13-7).

As these bacteria thrive under these conditions, they will continue to promote this reaction until failure of the pipe occurs. Aerobic bacteria

(sulphur bacteria) oxidize sulphur (present in their cells) to yield sulphuric acid, which attacks the iron. These grow best under acidic conditions (pH 0 to 1).

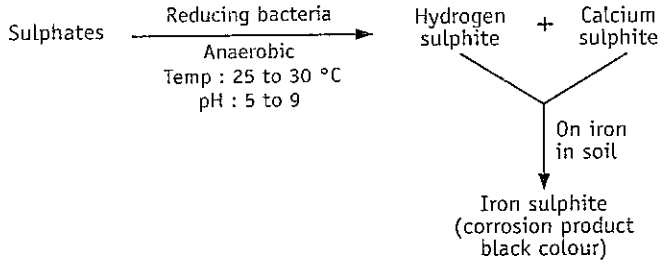


Figure 13-7. Sequence of events associated with the anaerobic sulphite reducing bacteria.

PREVENTION AND CONTROL OF CORROSION

Selection of Proper Material

Corrosion should not be permitted in fine mesh wire-screens, orifices and other items in which dimensions are critical and changes are not permitted. In many cases, non-metallic materials will be useful and attractive from the point of view of economics and performance. These should be considered if their strength, temperature and design specifications are satisfactory.

The corrosion characteristics of chemicals and limitations of construction materials must be considered from the literature before selecting equipment. In addition, processing conditions to which the material is exposed should also be considered. For this purpose, relevant literature should be consulted. Permissible corrosion rates are important factors and differ with equipment. Appreciable corrosion can be permitted for tanks and lines, if anticipated and allowed for thickness in its design.

Proper Design of Equipment

In the design of equipment, a number of fittings such as baffles, stiffeners, drain nozzles, location of valves and pumps should be considered. Corrosion can be minimised, if the equipment design facilitates:

- Elimination of crevices.
- Complete drainage of liquids.
- Ease of cleaning.
- Ease of inspection and maintenance.

On the basis of these general principles, some poor and good engineering designs are given in Figure 13-8. A direct contact between two metals should be avoided, if they are separated widely in the electrochemical series. Otherwise, they should be insulated. Equipment should be supported

in such a way that it will not rest in pools of liquid or on damp insulating material.

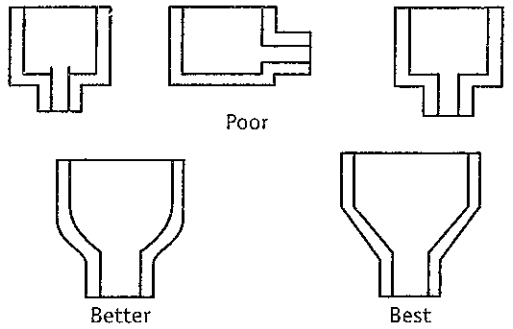


Figure 13-8. Drainage affects the corrosion.

Coatings and Linings

Nonmetallic coatings and linings can be applied on steel and other materials of construction in order to combat corrosion. Appropriate methods such as electroplating, cladding, organic coatings should be considered. The thickness of the linings is important (100 mils). Effective linings can be obtained by bonding directly to substrate metal or building multiple layers or lamination.

Organic coatings are used as linings in equipment such as tanks, piping, pumping lines and shipping containers. Some examples of the linings are:

- Ceramic
- Carbon brick
- Plastic
- Elastic
- Glass-coated
- Organic

A thin non-reinforced paint-like coating of less than 0.75 mm thickness should not be used in services for which full protection is required from corrosion. Some examples of linings and uses are:

Linings	*Uses*
Tin coated steel (tin plate)	food containers
Lead (Pb) coating (Terne plate)	roofings
Aluminium (Al) coated steel	high temp conditions
Zinc (Zn) coated steel	many atmospheric conditions

The cladding (i.e. mechanical bonding) of steel with an alloy is another approach to this problem. For instance, special glasses can be bonded to steel so that the liner is of 1.5 mm thick which is impervious. Equipment and pipings are lined in this manner and routinely used in severely corrosive acid services. The only limitation of this method is service behavior of the protective coatings.

Altering Environment

Corrosion can be combated or reduced by employing the following environmental conditions.

(1) Removing air from boiler feed water prevents the influence of water on steel.
(2) Reducing aeration prevents the formation of passive oxide film in stainless steel alloys by acidic media.
(3) Pumping of inert gas into solutions prevents the contact of air or oxygen as in case of nickel based alloys.
(4) Reducing the temperature.
(5) Eliminating the moisture.
(6) Reducing the velocity or turbulence.
(7) Shortening the time of exposure.

Addition of acid media should be done as a last step, so that maximum dilution can be obtained.

Inhibitors

The corrosion inhibitors are added to the environment for effectively decreasing corrosion of metals. These form protective films.

- Adsorption type, e.g. adsorbed on the metal.
- Scavenger type, e.g. remove corrosion agents.
- Vapour phase type, e.g. sublime and condense on metal surface.

Examples of inhibitors are given below.

Inhibitors	*Material protected in the media*
Chromates, phosphates, silicates	iron and steel in aqueous solution.
Organic sulphides, amines	iron and steel in acidic medium.
Copper sulphate	stainless steel in hot diluted solution of sulphuric acid

Inhibitors also interfere with the process of corrosion, namely scavenging of oxygen, hydrogen and reducing the diffusion of the constituents.

- The diffusion of H^+ ions is considerably decreased by organic inhibitors. E.g. amines, mercaptanes, substituted ureas and thioureas. These are cathodic inhibitors.
- Reducing agents eliminate oxygen from the corroding medium. E.g. sodium sulphite.
- Inhibitors retard the diffusion to the cathodic areas. E.g. magnesium, zinc and nickel salts.

Inhibitors are generally used in quantities less than 0.1 % by weight. In some cases, the amount of inhibitor used is critical.

Cathodic Protection

The cathodic protection is based on the galvanic action between the metal(s) of the plant (cathode) and anode suspended in the solution. The metal to be protected is made a cathode, i.e. electrons are supplied, there by dissolution of metal is suppressed. This can be achieved by two methods.

(1) Sacrificial anode method (2) Impressed emf method

Sacrificial anode method : In this method, anodes are kept in electrical contact with the metal to be protected (cathode). The anodes are sacrificed, since they go into solution (Figure 13-9). For example, for the protection of iron and steel tanks, the metals such as zinc, aluminium, magnesium and their alloys are used as sacrificial anodes. These are used in limited pH range when high solution rate is acceptable, since these are amphoteric.

Anode metal is selected from the electrochemical series amongst the metals present above the tank metal. The anode should not be poisonous and not detrimental to the product.

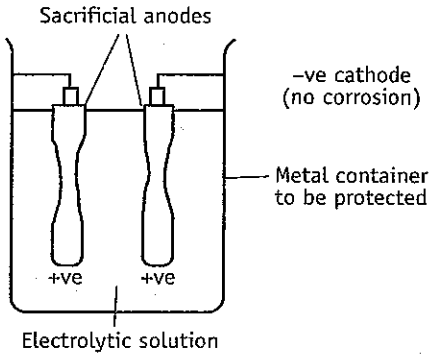


Figure 13-9. Simple sacrificial anodes.

Impressed emf method : This is also known as *applied current system*, i.e. external voltage is impressed between tank and electrodes. The negative terminal of power supply is connected to the material to be protected. Therefore, the natural galvanic effect is avoided and the anode is maintained positive (Figure 13-10).

The term 'impressed emf' (or current) means the current which is greater than the corrosion current. When such an impressed current is applied in opposite direction, the corrosion effect is nullified. Under such conditions, anode is converted to cathode in the corroding metal. Since anode is not consumed, any conducting material, metal or non-corrodable

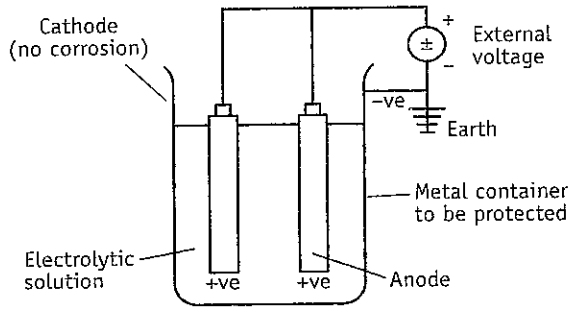


Figure 13-10. Impressed current cathode protection.

alloys can be used. For example, in case of sulphuric acid and deionised water, graphite and high silicon steel are impressed. The anodes can be buried in the ground or suspended in the aqueous solution of electrolyte.

Advantages : (1) This method is used for large tanks to store mild corrosive liquors. In these cases, mild steel is used with negligible corrosion.

(2) Cathodic protection method is simple and the most effective.

(3) It is inexpensive. It enables the use of cheaper material for plant construction.

Disadvantage : Corrosion cannot be reduced to zero.

Anodic Protection

In the method, a predetermined potential is applied to the metal specimen and the corresponding current changes are observed. During the initial stage, the current increases indicating the dissolution (corrosion) of the metal. When the current reaches a critical point, passivisation occurs, i.e. the oxide layer sets in a suitable oxidising environment. The potential at critical point is called *passivating potential.* Above this passivating potential, the current flow decreases to a very small value called passivating current.

The *passivating current* is defined as the minimum protective current density required to maintain passivisation.

Passivity is a phenomenon in which a metal or alloy exhibits much higher corrosion resistance than expected from its position in the galvanic cell. At this stage, an increase in potential will not corrode the metal since the latter is in a highly passive state. For example, in case of stainless steel, titanium becomes easily passive and cannot offer cathodic protection. In such cases, the corrosion rate may be slowed down by the use of anodic current.

Advantage : Anodic protection requires a small current. The anodic protection method is utilised in the transportation of concentrated sulphuric acid.

Disadvantages : (1) Corrosion cannot be reduced to zero.

(2) This method cannot be applied for metals, which do not passivate.

A proper material should be selected for a specific process based on the literature and by personal experience. The factors influencing corrosion will not only help in selecting the right kind of material, but also suggest the processing conditions. It is equally essential to identify the type of corrosion, if it occurs. Since the theories of corrosion are known, it is possible to adopt appropriate preventive measures.

Comment 13-8. Why is brass a preferred alloy for the construction of equipment?

Comment 13-9. A piece of pure zinc and impure zinc are placed in a salt solution, which will corrode faster. Why?

Comment 13-10. Highlight two non-metal linings on the material for the construction of equipment.

Summary

Corrosion is undesirable reaction occurring to a large extent on the surface of the equipment, which makes the equipment malfunctional. The corrosion reactions occur due to atmospheric conditions (air and oxygen) and also due to the experimental conditions (acids, catalysts, temperature, etc.). Normally, metals and to some extent alloys are affected and the equipment undergoes gradually electrochemical changes. Corrosion can occur by the direct contact of dry gases (dry corrosion) or due to attack of aqueous media on the metal (wet corrosion). Corrosion reactions occur on dies and punches, milling equipment, chemical processing reactors, fermentors, storage containers, etc.

Several theories are proposed for the causes of corrosion: a) the formation of galvanic cells (flow of electrons), b) flow of current from a more active metal and c) metal in contact with acidic media. Several factors affect the rate of corrosion: materials related (purity, physical state), solution pH (H^+ ions capture the electrons), oxidizing agents (oxygen to form oxide forms), temperature (phase changes and enhanced diffusion), velocity (formation of corrosive films or removal of protective films), nature of surface films (soluble, insoluble, submerged or dry), constituents of reaction media (sodium, chlorides, silicates, humidity) and other factors (concentration of chemicals).

Corrosion is broadly classified as general, localized, structural and biological corrosion. In general corrosion, the entire area of the equipment is affected and hence considered as physicochemical type or electrochemical type. Localized corrosion is the most frequently observed and occurs on different locations, such as intergranular (pitting corrosion and crevice corrosion), stress induced corrosion (cracking, fatigue and fretting corro-

sion), flow related corrosion (impingement, erosion and cavitation erosion), chemical reaction related corrosion (galvanic, oxygen and hydrogen embrittlement). In structural corrosion, the strength of the metal is reduced (alloy is removed or released). These are graphite corrosion and dezincification. Biological corrosion occurs as the metabolic products of microorganisms deteriorate the metal.

The first line of action for the prevention of corrosion is to select a right kind of metal or a nonmetallic material for the fabrication of the equipment. The literature gives sufficient information. Appreciable corrosion can be prevented for tanks and lines, if anticipated and allowance is made for thickness of the design. Corrosion can also be controlled by appropriate design, by avoiding crevices and promote complete drainage. Corrosion is prevented by applying nonmetallic coatings and linings on the metal equipment, reducing the environmental severity (pH, temperature, oxygen, moisture, etc.), adding the corrosion inhibitors (which can scavenge oxygen and hydrogen) and reducing the diffusion of the constituents. Cathodic protection and anodic protection methods also prevent the corrosion. In these methods, the diffusion of chemicals into the cathode or anode is prevented. A proper material and suitable experimental conditions are selected for a specific process, based on the literature and by personal experience.

QUESTION BANK

Each question carries one mark

Note: Encircle the alphabet which corresponds to the single best response.

1. A severe form of corrosion that develops in highly localized areas of metal surface is called as:
   A. erosion B. galvanic corrosion
   C. pitting corrosion D. stress corrosion
2. The ability of a metal surface to withstand repeated cycles of corrosion is known as:
   A. cavitation erosion B. corrosion fatigue
   C. erosion D. stress of corrosion cracking
3. Which one of the following CANNOT be used to combat corrosion?
   A. Increasing the temperature of storage
   B. Pumping of inert gas into solution
   C. Removing air from boiler feed water
   D. Shortening the time of exposure
4. One of the following types of corrosion is NOT related to liquid flow related corrosion.
   A. Cavitation erosion B. Erosion
   C. Fretting corrosion D. Impingement corrosion

5. Corrosion of metals is fairly high in one of the following medium.
   A. Acidic B. Alkaline
   C. Neutral D. Non-aqueous
6. Which one of the following types of corrosion of metals is flow related?
   A. Biological corrosion B. Crevice corrosion
   C. Erosion D. Inter-granular corrosion
7. For explaining dry corrosion of iron metal, which one of the following is necessary?
   A. Chlorine B. Hydrogen
   C. Oxygen D. Sulphur
8. For chemical (dry) corrosion of iron, which one of the following conditions is necessary?
   A. Connecting the metal through external wire
   B. Hydrochloric acid solution
   C. Sulphur dioxide gas
   D. Sulphur dioxide solution
9. Galvanic corrosion is observed, when external electric current in solution is passed between one of the following combinations.
   A. Gold and platinum B. Iron and hydrogen
   C. Iron and iron D. Zinc and copper
10. Increase in temperature does NOT enhance the extent of corrosion by one of the following conditions.
    A. Diffusivity of the corroding medium
    B. Solubility of the constituents of the metal in the corroding media
    C. Thickness of the oxide film.
    D. Volatility of the constituents of the metal
11. The corrosion of aluminum metal is prevented, due to one of the following film characteristics.
    A. Thick and nonporous film B. Thick and porous film
    C. Thin and nonporous film D. Thin and porous film
12. In cathodic protection, one of the following effects is suppressed.
    A. Dissolution of anode B. Dissolution of cathode
    C. Dissolution of oxide film D. Electric current
13. Which one of the following conditions is NOT responsible for preventing the corrosion?
    A. Inhibiting the flow of current B. Decreasing the temperature
    C. Removing air and oxygen D. Removing inhibitor
14. Anodic protection controls the corrosion based on one of the following mechanisms.
    A. Adding inhibitors B. Decreasing the current flow
    C. Drainage of liquid D. Promoting oxide layer

15. Which one of the following metals can retard the corrosion of metals?
    A. Carbon steel B. Chromium
    C. Iron D. Zinc

Each question carries 2 marks

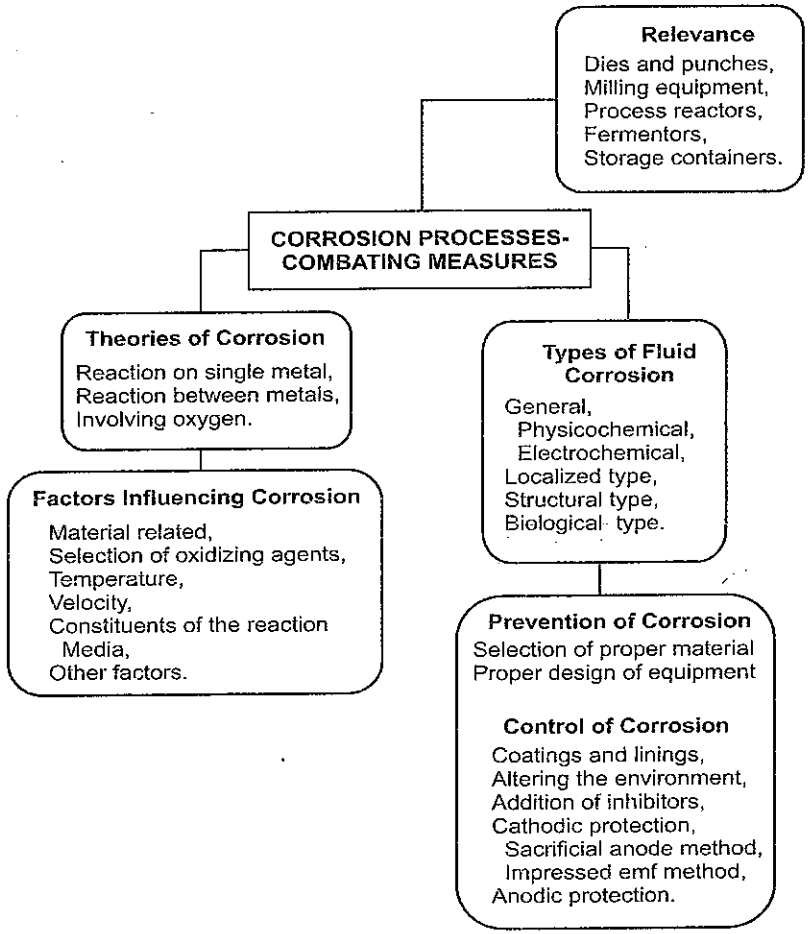
1. Explain the terms 'pitting corrosion' and 'galvanic corrosion'.
2. Give the applications of protective linings and coatings with respect to corrosion control with suitable examples.
3. What is the role of plastic washers in the corrosion of metals?
4. How are oxide films formed? What are its advantages?
5. Highlight the role of oxygen in the corrosion of metals.
6. Explain the role of temperaure on the metal corrosion.
7. Differentiate between chemical corrosion and electrochemical corrosion.
8. Explain the term 'rusting of iron'. What is its chemical formula?
9. Describe the term 'passivity'. How is it combat corrosion?
10. Explain the effect of pH on corrosion.
11. Describe the effect of grain size of the metal on corrosion.
12. In a structure, two dissimilar metals should not be allowed to come in contact with each other. Why?
13. Which type of oxide film is more protective against corrosion? Give one example of a metal, which produces such an oxide film.
14. How does the addition of amines protect against corrosion of iron.

Each question carries 5 marks

1. What is meant by corrosion? Mention the factors that influence rate of corrosion.
2. Explain measures you suggest to check the problems of corrosion.
3. Write the electrochemical theory of corrosion.
4. Describe the biological corrosion and suggest the preventive measures.
5. Describe the mechanism of corrosion of iron.
6. Define corrosion. Give its causes. Classify corrosion.

Each question carries 10 marks

1. What is meant by corrosion? Name the various types of corrosion. How can corrosion be prevented?
2. Describe various types of corrosion and suggest the methods to tackle the same in pharmaceutical industries.



MINDMAP DETAILS OF CORROSION PROCESS-COMBATING MEASURES

CHAPTER 14

Transportation of Solids

Belt Conveyors
Screw Conveyors
Pneumatic Conveyors
Chain Conveyors
Bucket Conveyors
Selection of Solid Transportation Equipment
Storage of Solids

LEARNING OBJECTIVES

After reading this chapter, the reader should be able to:

- Understand the methods of conveying of solids in the context of automation in the industry.
- Explain the construction, working and applications of belt, screw, chain and belt conveyors.
- Describe the elements involved in the construction of pneumatic conveyor and applications.
- Select an appropriate solid transportation equipment, based on the characteristics of materials.

The term '*conveying*' is also applied to the transportation of solids.

The transportation of liquids is much simpler, cheaper and less troublesome than handling solids. In many operations, solids are handled in a finely divided state, so that they remain suspended in a stream of fluid. However, such a system is not suitable for handling all types of solids. Therefore, it may be necessary to study the transport solids as such. This unit operation is important in the storage and handling of raw materials, finished products and packed goods. The advantages and objectives are given below.

Efficient and Effective Conveying—Objectives and Advantages

1. Decreases product costs and increases manufacturing capacity.
2. Decreases cost of raw material. For example, penalty charges are levied when cars are not loaded or unloaded according to schedules. Losses due to spillage or torned containers is reduced.

3. Decreases processing time and conservation of energy.
4. Rigid in-process controls leading to decreased quality control and quality assurance costs.
5. High degree of uniformity, reproducibility of the process and compliance with the cGMP regulations (current good manufacturing practices).
6. Minimum contamination and dust formation.
7. Increases employee safety and reduces labour costs.

If raw materials are not moved as required by production schedules, the manufacturing process will be slowed down. In addition, machine time and operation time will be wasted. As a result in-process inventories will be increased.

Improper handling and storage can lead to damage, outdated and loss of materials. Improper handling of granules, strips, bottles and chemicals can place employees in physical danger. This can often lead to employee frustration and reduced morale due to constant production delays.

In today's world of automation, solid transportation has drawn a greater attention. It is often necessary to prevent the contact of material with the persons, in order to avoid contamination (as in case of antibiotics). Similarly working personnel should not be exposed to poisonous and obnoxious substances. Therefore, a closed conveying system is essential. Therefore a closed manufacturing operation system is needed and calls for automatic handling systems. The feeding of materials into a reactor is always done mechanically. Similarly, discharge should also be made automatic. Conveyors are used in the production of most dosage forms such as tablets, capsules, liquid orals and injections.

Solid transportation systems (conveyors) are classified into five major groups. These are:

1. Belt conveyors
2. Screw conveyors
3. Pneumatic conveyors
4. Chain conveyors
5. Bucket conveyors

A few important conveyor systems, construction, working and applications are discussed in this chapter.

Comment 14-1. Why improper handling of materials must be avoided?

BELT CONVEYORS

The basic elements of the belt conveyor are:

1. Belt and belt tightening system
2. Belt drive and power supply

3. Roller supports for belt
4. Feeding arrangement
5. Discharge arrangement

Principle

Horizontally or inclined placed motor driven rotating belt on pulleys conveys the material from feeding point to discharge point.

Construction

The construction of a belt conveyor is shown in Figure 14-1. Belt conveyor consists of a core or carcass (meaning skeleton or backbone for the belt) of several piles of cotton duck, each layer is impregnated and bonded with rubber. The carcass is then covered with a thin layer of rubber that binds the piles together. Both ends of the belt are joined together, so that the belt can rotate continuously. The belt may run horizontally or slightly inclined from the feed point.

- If the belt is too thin for its width, it will sag between idlers.
- If the belt is too thick, it does not trough properly.

Sometimes, the length of belt is increased due to a variety of factors such as temperature and humidity of the ambient. In such cases, it is necessary to keep the belt taut. Hence, tighteners (or take-up) are installed to maintain an even-tension on the belt under all conditions. The simplest take-up consists of a cast iron bed with a travelling block moving along a screw.

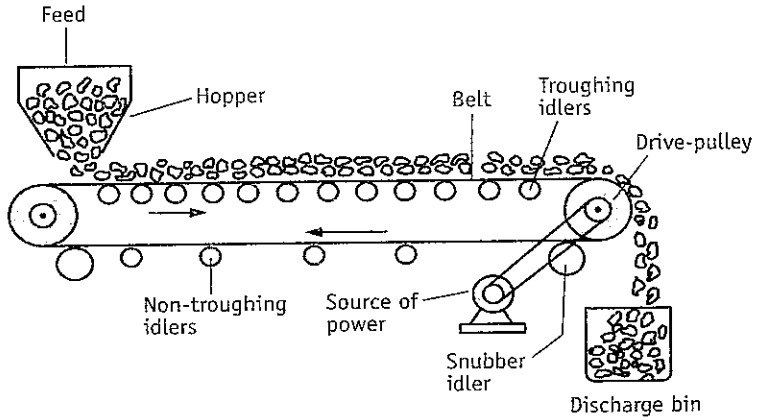
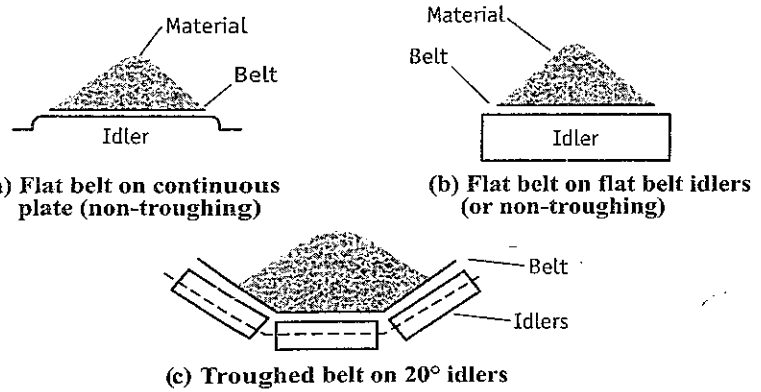


Figure 14-1. Construction of belt conveyor system.

The belt is allowed to move with the help of a *belt drive*. The simplest belt drive is a bare steel pulley actuated with some source of power. The drive of the belt conveyor is fixed at the discharge end (It is rarely arranged

at the feed end). There should be appropriate contact between the belt and pulley. Introducing snubber idlers just below the pulley can increase the contact.

The belt is supported by rollers, which are arranged on a shaft. These are called *idlers*. The idlers are carried on bush bearings lubricated with grease-cups. The idlers are generally troughed to depress the belt at the centre and rise at the edges (Figure 14-2c). This permits the belt of a given width to carry more material per linear metre without spillage. The belt returns on ordinary and non-troughing rolls.



(a) Flat belt on continuous plate (non-troughing)

(b) Flat belt on flat belt idlers (or non-troughing)

(c) Troughed belt on 20° idlers

Figure 14-2. Construction of support idlers in width-wise description.

A hopper is placed at one end in such a manner to load the feed at the centre of the belt. Cleaning devices such as rotating brush and rubber scrapper blades are placed in the path of the belt in order to clean, if the material sticks to the belt. Provision is made at the other end for discharging.

Working

When power is applied to a conveyor, the belt starts rotating. As the pulley moves, the belt begins to travel in forward direction, because of its close contact with the pulley. Snubber idlers also help in maintaining the close contact between the pulley and belt.

The material (to be transported) is loaded on its centre of the belt with the help of a hopper. The material travels along the belt. The belt moves forward on troughing idlers. This permits the belt to carry more material per linear metre without spillage. The amount of feed delivered depends on the width and speed of the belt. At the discharge end, the material may be unloaded manually or mechanically.

Once the material is unloaded, the belt returns on lighter non-troughing rolls to the point of feeding.

Pharmaceutical Applications

Belt conveyors are used in transporting containers for filling, capping, sealing, labelling, pasting, visual inspection, etc. in the production of injectables, liquid orals, ointments and jellies. In the strip and blister packings of tablets and capsules, strips are conveyed on a moving belt. During this process, the strips are packed in the cartons.

Belt conveyors are used in the manufacture of lozenges. It is a continuous process of candy base cookies. When a mass of sugar base is on the conveyor, the water is removed. At the end of the belt, the candy base is mixed, tempered, formed, roped, melted, acidulents and flavours are added, cooled and sized.

Advantages:

(1) Belts can be made of asbestos fibres, neoprene, teflon and vinyl polymer. Cord belts are also used.
(2) Belt conveyors are for general purpose installation and available in relatively large sizes. These can travel several kilometres as in case of coal mines.
(3) Routine maintenance of belt conveyor is easy.
(4) Belt conveyor is economical in terms of cost per unit tonne that it can handle.

Disadvantage:

- Belt conveyor is expensive.

Selection of Belt Conveyor

The capacity of a belt conveyor depends on the cross section of the load and the speed of the belt. The cross section of the load depends on the width and slope of the belt and size of the material. The selection of a belt conveyor depends on:

- Power required.
- Mechanical and tensile strength of the belt system to handle the wide varieties of materials.
- Lump size.
- Troughability of the belt.
- Ability of the belt to support the load between idlers.
- Chemical resistance of the belt to the material to be handled.

Manufacturers of belt conveyors publish charts or formulae for the construction of conveyors, size and power requirements.

Comment 14-2. Idlers are the essential components of belt conveyor. Explain.

Comment 14-3. Belt conveyor is suitable for transporting materials when the path of travel involves many turns and lifts. True or false. Justify.

SCREW CONVEYORS

The basic elements of the screw conveyor are:

1. Trough system
2. Flights and power supply
3. Feeding arrangement
4. Discharge arrangement

Principle

Horizontally or inclined or vertically placed motor driven screw like flight conveys the material in the trough from the feed point to discharge point.

Construction

The trough is a U-shaped vessel in which the material is enclosed during conveying (Figure 14-3). The trough is usually made of a sheet of steel and available in standard lengths. If a trough of more length is required, then more number of such units are joined together.

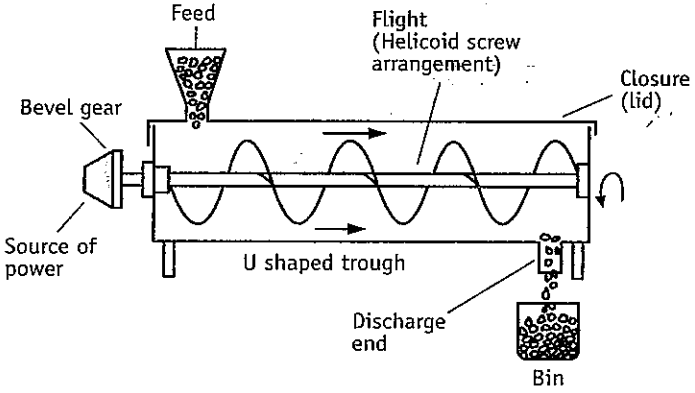


Figure 14-3. Construction of a typical screw conveyor.

Screw element usually consists of a spiral blade (conveying mechanism is like a screw), which is called *flight*. The simplest form of the flight is the sectional conveyor. Helicoid flight is shown in Figure 14-3. It is made of a single long ribbon that is twisted and wrapped into a spiral shape. These standard flights are welded to the central shaft. Alternatively the conveyer element (helicoid flight element) is suspended with the help of hangers along the length of the trough. Usually one hanger is used for each flight section. Hangers contain bushings of white cast iron, so that lubricants need not be used.

The drive end and discharge end are known as *box-ends*. At the drive end, shaft is connected to bevel gears. Power is transmitted through the shaft to the flight. The shaft is rotated around an axis and remained nearer to the bottom of the trough. The feed is normally introduced by plain spout,

which gives uniform flow of material. At the discharge end, arrangement is made to receive the material using open-end trough or open-bottom trough.

Working

When power is applied, the drive rotates the shaft through the bevel gears. The screw element starts rotating. The flight is rotated round an axis and remained nearer to the bottom of the trough. Feed is normally introduced by plain spouts. The material will be trapped between the gaps of the spiral blade. As the flight moves, the material also moves forward along the path of the sections. The material is received through open-end trough or open-bottom trough.

Applications:

(1) Screw conveyor is used for transporting finely divided solids or pasty solids.

(2) Materials having properties such as light-weight, medium-weight, abrasive and non-abrasive can be easily handled using screw conveyor. It is a versatile conveyor system.

(3) Special flights and casings are available for operations, such as mixing, de-watering, heating and cooling.

(4) It has the capacity to handle the materials of about 280 m^3/h.

Advantages:

(1) Materials can be conveyed horizontally, vertically or inclined.

(2) Screw conveyors are easy to operate and occupy less space.

(3) Different constructions are available and can be adapted for a variety of materials. Screw conveyors can be fabricated in a variety of materials ranging from cast iron to stainless steel.

(4) Screw conveyor can be operated at positive and negative pressures.

(5) High and low temperatures can be maintained by insulating the casing.

(6) Since it is a closed system, the environment becomes dust-free.

Disadvantages:

(1) Screw conveyors operate at relatively low rotational speeds.

(2) Extremely cumbersome handling when conveyor becomes larger.

(3) At high speeds, abrasive problems arise.

(4) Power consumption per unit weight transferred is high.

Selection of Screw Conveyor

The size and speed of a screw conveyor are determined to make a choice of the design. The type of construction depends on the requirements such as:

- Scale of operation
- Severity of service
- Value of the material

Comment 14-4. What are the special features that make a screw conveyor necessary in the pharmaceutical industry?

PNEUMATIC CONVEYORS

The basic elements of the pneumatic conveyor are:

1. Air supply (or vacuum) system
2. Air slide and pipeline
3. Feeding arrangement
4. Discharge arrangement (air and feed separation)

Principle

When a high velocity air is passed through a bed of solid particles, the individual particles are dragged by the air. Finally they are suspended in the air. Such a system is known as fluidized bed, which is described as a condition of fully suspended particles. In this condition, the suspension behaves like a dense fluid and can be transported from one point to another in processing plants. At the discharge end, the gas is separated and the solids are recovered.

Construction

The construction of a pneumatic conveyor is shown in Figure 14-4. Fans or cycloidal blowers are connected to the conveying system. An air slide consists of a chute with a porous base through which air passes. The path of material travel may vary from a few metres to several hundred metres. Conveyor mechanism can be operated for horizontal and vertical distances. The material supply (feed) is connected to the air slide through a rotary feeder valve. The other end of the pipeline is connected to a cyclone separator.

Working

The cycloidal blowers (or fans) produce air at pressure about 7.0 kilopascals. This air is passed through the air slide at the rate of 1.5 metre per minute into the pipeline. During this process, the rotary feeder valve rotates and allows the feed to enter the pipeline. These solids are suspended into a stream of air in a *fluidised state* until it reaches the receiving end.

The material is then admitted to cyclone separator to remove large particles and fine particles, if any. The large particles are collected into the bin. The fine particles are trapped in a bag filter. The gas can be recycled to the blower inlet in a closed system to save the valuable gas. These systems are used for free flowing materials.

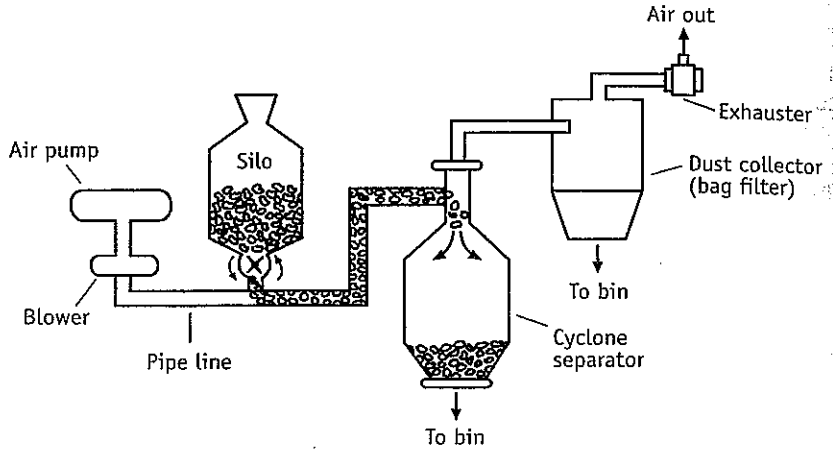


Figure 14-4. Pneumatic conveying system, pressure type.

For the proper design and satisfactory operation of pneumatic conveying, it is necessary to know about characteristics of powders such as density, particle size distribution, cohesiveness, angle of friction, angle of repose and fluidization.

Applications:

(1) Pneumatic conveyor is the most important handling system in chemical industry.
(2) It is used in the formulation of powdered insufflations.
(3) Generally, light and bulky materials such as grains can be transported easily.
(4) Pneumatic conveyor is used for handling of unpleasant and injurious (toxic) materials, since it is a closed system.
(5) Powders containing poisonous constituents can be transported.
(6) Fine powders and pellets having the size up to 6.0 millimetres and bulk densities from 16 to 3000 kg per metre cube can be handled by pneumatic conveyor.

Advantages:

(1) While conveying the material, sometimes the path may involve many turns and lifts. In such cases, other types of conveying become costly.

(2) Pneumatic conveyor is economical compared to other types of conveyors.
(3) Friction losses are small, because there are no movement of mechanical parts.

Disadvantages:

(1) The pneumatic conveyor needs more power than other types of conveyor systems.
(2) Erosion of internal surface of the vessel and attrition of solids may take place.
(3) Uneven contact of gas and solids is observed.

CHAIN CONVEYORS

Chain conveyor consists of two elements, viz., chain elements and chain attachments. Chain elements are made of malleable cast iron or stainless steel. These links are so cast that they can be assembled and detached without use of tools. Chains are endless and move continuously. The material is loaded into a suitable container and placed on the chains. These are usually constructed on the job.

Advantages : Chain conveyor is a cheap and simple piece of equipment. It can be adapted to a wide variety of problems.

Scraper/Flight Conveyors

Flight conveyor consists of one or two endless chains passing through a trough or a set of guides. The chains have plates of wood or steel called *flights* attached at regular intervals. The flights are shaped to fit the troughs. The chains pull the flights and the material along the trough and passes over sprockets at the end of the run. One of the sprockets acts as the drive. In an elaborate form, flight conveyor is supported by two chains of roller pintle type (Figure 14-5). Scraper conveyors with speeds of 30 m/min are common, but the speed may range from 8 to 60 m/min.

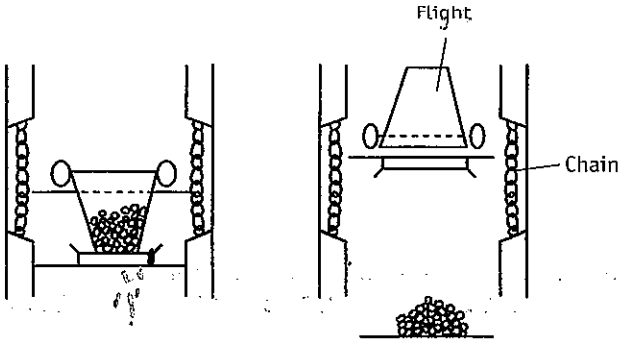


Figure 14-5. Scraper/flight conveyor with two chains.

Uses : Scraper conveyor is widely used for loose material that is non-abrasive, such as grain, food-waste, garbage, sawdust, chips and coal. Chain conveyors can be used in pharmaceutical industry for the materials similar to the ones mentioned earlier.

Advantages : Scraper conveyor is the simplest and cheapest type. The cost of installation is also low. Scraper or flight conveyors have greater adaptability to a wide variety of conditions. It is suitable for steeper situations that are not possible by belt conveyor (inclination 45°).

Disadvantages : Scraper or flight conveyor needs heavy power requirements. Repairing charges are high. It is not suitable for friable abrasive material such as clinkers, gravel and crushed ore.

Apron Conveyors

Apron conveyors are usually used for transporting heavy loads and short runs, at low speeds. The simplest apron conveyor consists of two endless roller chains, which are connected by double beaded steel pans. The beading prevents the material from slipping backward when conveyor is inclined. Wooden or metal boxes are fixed between the chains and the whole conveyor drags on the support. Apron conveyors are used for conveying material such as lumpy, abrasive and hot, provided that these are not injurious to flexible belts.

BUCKET CONVEYORS

Principle

Horizontally, inclined or vertically placed motor driven chains carrying buckets convey the solid material from the feed point (boot) to the discharge point.

Construction

Buckets are used for loading the materials. The buckets are made of cast iron or stamped steel and available in many forms. Flat buckets are used for materials that are sticky. Heavily stamped steel buckets are employed for large lumps, for example, coal and crushed stone.

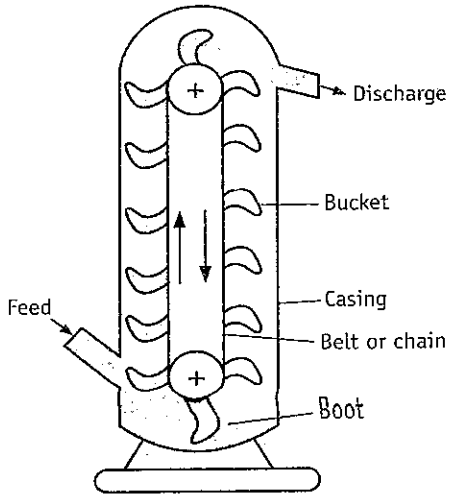


Figure 14-6. Construction of a bucket conveyor.

The buckets are attached to belts or chains. The chains are endless and buckets are riveted between two chains (Figure 14-6). The chains are generally long pitch, straight and side type. The buckets are spaced to prevent interference in loading and unloading. For heavier loads, two chains may be used. The attachments are slightly above the level of the chain so that the ends of the sprocketed booth do not strike the back of the buckets.

The weight of the materials in the conveyor results in the stretching of the chain. Therefore, tightening devices are generally provided for altering the position of the sprocket at the foot of the elevator.

- In *horizontal runs*, buckets overlap each other and the feed is introduced as a continuous stream of material.
- In *vertical lines*, the buckets are pivoted in such a way that they hang freely between the chains. Therefore, conveyor acts as an elevator.

At the foot of the elevator, a structure known as 'boot' is used for feeding the buckets and also for tightening the chains. Buckets are sometimes completely enclosed in a casing. The casing is made of wood or steel sheet.

Working

The elevators are generally driven from the head sprocket. At the foot of an elevator, 'boot' helps in feeding. The buckets are normally fed by digging into the materials particularly in case of loose material and granular solids. The buckets maintain their carrying capacity by gravity, but they can convey the material horizontally or vertically or any desired path. Loading can be done by the flow of material through a chute into the buckets. Buckets may be readily discharged at any point by a tripping device, causing each bucket to turn through 90 degrees. The types of discharges are continuous, positive and centrifugal.

Applications : Bucket conveyors are used in transporting coal, crushed stone, grains, etc.

Advantage : Bucket conveyors are very flexible.

SELECTION OF SOLID TRANSPORTATION EQUIPMENT

Varieties of solid transportation equipment are available in the market. Some of them are for general-purpose use, while others are for special purpose use. The choice of equipment depends upon specific requirements of the industry.

The best equipment is one that:

- permits smooth and continuous production flow
- involves less number of accidents

- reduces production cycle time
- promotes better working conditions
- lessens fatigue to the operators
- brings down total material handling costs

The following factors may be considered, while selecting an equipment for the transportation of solids.

Materials to be Moved

The size, weight, delicacy, nature (solid, liquid and gas) of material and the chances of getting damaged during transportation of solids should be considered. Accordingly a flexible system should be installed.

Plant Building and Layout

The type of building may exert a single greatest influence on the material handling system. A multi-storeyed building facilitates the use of gravity for material flow. The door locations, sizes, ceiling heights, roof and floor strengths, stairs, columns, width of aisles, etc. influence the choice of the equipment. For example, weak roof ceiling prevents the usage of overhead conveyors.

Production Machines

Different machines have different outputs per unit time. The equipment should be able to handle the maximum output.

Type of Material Flow Pattern

A vertical flow pattern requires elevators, conveyors, pipes, etc. whereas horizontal flow pattern needs trucks, overhead bridges, cranes, conveyors, etc. Gravity is the cheapest. The movement of material from top to bottom through multileveled facilities is the most efficient way of moving materials. Therefore, multi-storeyed building is utilized for production. An efficient movement of material is possible along the straight lines, a direct path to its destination.

Type of Production

Conveyors are more suitable for fixed routes for continuous process and powered trucks are ideal for batch operation. Conveyors, though costly, can handle more volume of production per unit time as compared to trucks. But trucks are more flexible equipment.

Cost of Equipment

The initial costs of conveying equipment are high. When human contact with the product must be minimized, equipment is the only alternative, hence cost does not limit the installation. However, working cost of equipment is sometimes less. The maintenance as well as useful life and the scrap value of the equipment must be weighed against advantages.

Handling Costs

Economy in solid conveying can be achieved by employing gravity-aided movements and minimizing the distance of material travel. A system that allows the product to directly fall over the equipment is more ideal. Such measures beat the purchase cost of the equipment.

Life of Equipment

Periodic inspections, repairs and maintenance of equipment increase its life, facilitate smooth flow of materials and economize the production system. The amount of care and maintenance that is required for the material transporting equipment is important.

STORAGE OF SOLIDS

Attention must be paid to the storage of solids. Storage is an important operation, if the material is too valuable or too soluble when exposed to atmosphere as in outdoor piles. The following are used for storing solids.

Bunkers : These are used for storage of pulverised solid material. During plant shut down, the solid material is stored in bunkers. Coarse solids such as gravel and coal are stored outside in large piles, unprotected from the weather. Out-door storage can lead to environmental problems such as dusting and leaching.

Hoppers, bins and silos : A *bin* is fairly wide and not so tall. It is a cylindrical or rectangular vessel of concrete or metal. A *silo* is tall and relatively small in diameter. A *hopper* is a small vessel with a sloping bottom. It is used for temporary storage before feeding solids to a process. These containers are loaded from the top by some kind of an elevator and discharged ordinarily from the bottom.

Now-a-days, there have been extensive improvements in the use of solid conveying equipment. For example, granulation and tabletting operations are completely automated and computer controlled. The above system utilizes pumps and bucket conveyors to move materials upward whenever required. Examples are transporting granules and transporting compressed tablets for batching and film coating. These use belt conveyors and pneumatic conveyors to move the material horizontally.

Comment 14-5. What is the difference between the bins and silos?

Summary

Transportation of solids is a troublesome unit process. When solids are available in a finely divided state, these can be suspended in a stream of fluid and such a process mimics the transportation of fluids. However, such a system is not suitable for handling all types of solids. In the today's

world of automation, solid transportation has drawn greater attention. Further, a closed system of conveying is ideal to avoid contamination and chemical hazards. A few solid transport systems are routinely employed in the pharmaceutical industry. Conveyors are used in the production of most of the dosage forms, such as tablets, capsules, liquid orals and injectables.

Belt conveyor, horizontal or inclined, is a motor driven rotating belt on pulleys and convey the material from feeding point to the discharge point. These are used in transporting the containers (bottles, ampoules, vials, etc.) for operations: filling, capping, labeling, pasting, visual inspection, packaging, lozenges, candy based cookies, etc. Screw conveyor moves the materials in a trough from feed end to the discharge end. High and low temperatures can be maintained and it can be made as a closed system. It is used for mixing, dewatering, heating and cooling. It can transport the finally divided solids and pasty solids. Chain conveyors are widely used for loose materials that are nonabrasive, such as grains, chips and coal. Apron conveyors are used for transporting lumpy, abrasive and hot materials. Bucket conveyors are chain driven and used for transporting coal, crushed stone, grains, etc.

In pneumatic conveyor, finely divided solids are suspended in a steam of air (fluidized state) and allowed to transport from one place to another. The characteristics of powders influence the proper design of pneumatic conveyor. This is used in the solid handling of chemical industry, formulation of powdered insufflations. It is a closed system and easy to make turns and lifts. Several varieties of solid transportation systems are available, a few are general purpose and others are specific purpose. The choice of a system depends on: the material, the machine, the plant building, cost, etc. Belt conveyor and pneumatic conveyors are used to move material horizontally. Therefore the construction, working, advantages and disadvantages are understood to utilize these systems effectively and efficiently.

QUESTION BANK

Each question carries one mark

Note: Encircle the alphabet which corresponds to the single best response.

1. The term 'conveying' is applied to transportation of one of the following substances.
   A. Fluids B. Gases
   C. Liquids D. Solids
2. The belt conveyor moves mainly with the help of:
   A. drive pulley B. idlers
   C. non-troughing idlers D. snubber idlers

3. In belt conveyor, the main role of idlers is to:
   A. make the belt under even-tension
   B. move the belt forward
   C. support the belt
   D. withstand the weight of materials
4. Idlers are generally troughed (depress the belt at the center and rise at the edges), for:
   A. carrying more material without spillage
   B. giving the belt good shape
   C. reducing the risk of working
   D. sagging of the belt
5. In belt conveyor, snubber idlers also help to maintain a close contact between the following.
   A. Belt and hopper B. Belt and non-troughing idlers
   C. Idlers and belt D. Pulley and belt
6. In belt conveyor, the belt is NOT constructed with one of the following materials?
   A. Asbestos fibre B. Cotton
   C. Plastics D. Wood
7. Working efficiency of belt conveyor mainly depends on:
   A. load and speed of belt
   B. mechanical and tensile strengths of the belt
   C. power supplied and nature of idlers
   D. width and slope of the belt
8. In the construction of a screw conveyor, which is used for the movement of solid materials?
   A. Air pump B. Flight
   C. Idlers D. Pulley
9. The flight used in a screw conveyor is:
   A. round B. semicircle
   C. spiral D. square
10. In a belt conveyor, the carcass is usually impregnated and bonded with one of the following materials.
    A. Iron B. Plastic
    C. PVC D. Rubber
11. Pneumatic conveyor is used for the transportation of one of the following materials?
    A. Abrasive materials B. High density materials
    C. Pasty solids D. Toxic materials

12. Which one of the following is relatively simple, flexible and cheap conveyor?
    A. Belt type B. Chain type
    C. Pneumatic type D. Screw type
13. In the manufacture of lozenges, one of the following conveyors is used?
    A. Belt B. Chain
    C. Pneumatic D. Screw
14. In which type of conveyor, operations such as mixing, de-watering, heating and cooling can be adopted with special arrangement of accessories?
    A. Belt type B. Bucket type
    C. Pneumatic type D. Screw type
15. In which type of conveyor, fans or cycloid blower is connected?
    A. Apron type B. Bucket type
    C. Chain type D. Pneumatic type
16. Name the preferable conveyor system used for transporting unpleasant and injurious (toxic) materials?
    A. Belt conveyor B. Bucket conveyor
    C. Chain conveyor D. Pneumatic conveyor
17. Which type of conveyor is used in the formulation of powdered insufflations?
    A. Belt type B. Bucket type
    C. Chain type D. Pneumatic type
18. The term 'silo' refers to a storage system which has:
    A. fairly wide and not so tall
    B. outdoor bunker
    C. small vessel with sloping bottom
    D. tall and relatively small diameter
19. Which is the type of conveyor normally used for heavy loads and short runs?
    A. Apron type B. Belt type
    C. Bucket type D. Screw type
20. In the strip and blister packing of tablets and capsules, strips are conveyed through one of the following conveyors?
    A. Belt conveyor B. Bucket conveyor
    C. Chain conveyor D. Pneumatic conveyor
21. Which of the following is NOT the basic element of a pneumatic conveyor?
    A. Air slide B. Air supply
    C. Feed arrangement D. Flights

22. Which is the conveyor used for transporting grains?
    A. Belt conveyor B. Bucket conveyor
    C. Pneumatic conveyor D. Screw conveyor
23. In which conveyor, friction losses are low?
    A. Belt conveyor B. Bucket conveyor
    C. Chain conveyor D. Pneumatic conveyor
24. Which one of the following terms is given at the bottom of bucket conveyor?
    A. Base B. Boot
    C. Carcass D. Core
25. The drive end and discharge end in a screw conveyor are generally known as:
    A. box ends B. plight ends
    C. lid ends D. trough ends

Each question carries 2 marks

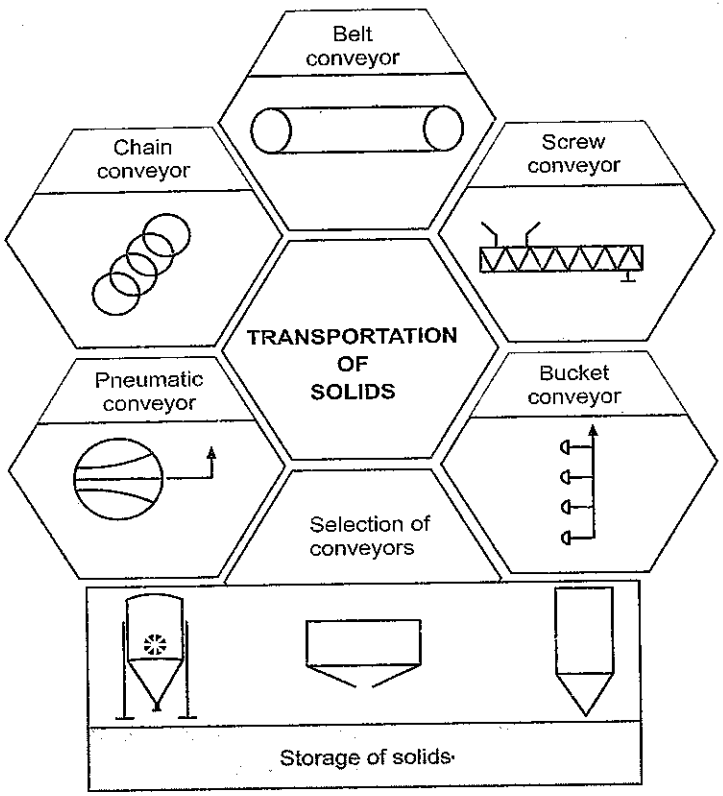
1. List two objectives of conveying of solids.
2. Name the conveyor suitable for transporting solids: a) to a long distance and b) to elevate large quantity of materials in a closed condition.

Each question carries 5 marks

1. Illustrate the concept of solid transport by fluidisation.
2. Describe the principle of pneumatic conveyer with a labelled diagram.
3. Describe the different types of conveyors used in pharmaceutical industry.
4. List advantages of screw conveyor and screw elevator. How do you compare these with pneumatic transport of solids?
5. Describe the construction and working of a screw conveyor.
6. Write the principle of belt conveyor with a neat diagram.

Each question carries 10 marks

1. Describe the construction and working of belt conveyor system for solid transport.
2. Name the devices used for transportation of solids. Describe pneumatic conveyor.
3. Describe the factors influencing the selection of transportation equipment for solids.



MIND MAP OF ON THE TRANSPORTATION OF SOLIDS

APPENDIX-I

Answers to the Comments

Chapter 1 : Industrial Processing

Comment 1-1. What is the difference between unit operation and unit process?

A unit operation is based on certain scientific principles. Size reduction (physical process) and hydrolysis reaction (chemical process) are unit operations. Unit operations can be used in diverse processes. Unit process involves a series of unit operations carried out sequentially to achieve objectives. Unit process is generally considered as a unique from the point of efficiency and economy. Examples are: manufacture of common salt and production of paracetamol.

Comment 1-2. Explain a method for calculating the yield of a product.

Material balance method is used for calculating the yield of the product. The mass of input (material) going into the process and mass of output (desired material) are considered. The unconverted raw materials and the production losses are also considered for mass balancing. Then yield of *the product* is obtained and validated.

Comment 1-3. Which are the expressions of reactants used for evaluating mass balance of a chemical process?

Molality and mole fraction expressions are applied for evaluating the mass balance. Molality is the term used to describe the quantities of each reactant. Molality does not change with temperature or the volume of the solvent. It is expressed in terms of weight of a solvent. It also includes the molecular weight of the substance (i.e. mole). Mole fraction is used in theoretical considerations.

Comment 1-4. Tie substance is an inert substance added to a process in order to account mass balance. True or false. Explain.

The statement is false. Tie substance is not inert, but reactive. Tie substance is not a substance added to the process. It enters the process and also leaves the process unchanged at the end. This substance helps in evaluating the material balance calculations.

Comment 1-5. What are the principles used for accounting losses due to friction in a process?

The principles of law of conservation of energy are applied for accounting the energy balance. During the fluid flow, the nature of pipe (rough, bend, non-uniform, etc.) offers friction to flow. These are accounted in the form of energy and all forms of energy are identified and balanced.

Comment 1-6. Differentiate between equilibrium and steady state.

Equilibrium means the rates of forward and backward reactions are the same. In other words, the reactions can proceed in opposite directions (reversible). In steady state, the process is in one direction. In both the cases, the parameters do not change with time. Equilibrium is a spontaneous process (chemical process), whereas steady state is maintained manually by the operator.

Comment 1-7. Understanding the magnitude of values is important, while applying the conversion factor. Explain.

Normally a conversion factor is used to convert a numerical value in one system into a corresponding numerical value in another system. The available numerical value may be high in one system, but when converted into another system, the value may be small. In such a case, conversion factor may have a low value. For example, 12 J is to be converted into calories. The conversion factor would be small, because in joules, the numerical value must be high (12) and upon conversion the result must be small (less than 12). The conversion factor is 0.239. Then in calories: $12 \times 0.239 = 2.868$ cal (small compared to 12 J numerically). Thus it is necessary to imagine the magnitude of the value after conversion. In the reverse situation, the conversion factor would be high. For example, 3 calories is to be converted into joules. The conversion factors must be high: $(1/0.239) = 4.184$. For 3 cal, the value is $3 \times 4.184 = 12.552$ J. The conversion factors are given in standard tables in encyclopedia.

Comment 1-8. When dimensionless equation is available for a particular process, conversion factor is not required. True or false. Explain

The statement is true. In a dimensionless equation, the net parameter does not has a unit, but individual terms in equation may have dimensions. Ultimately, these dimensions (terms) get cancelled. The net value is a number (numerical) and hence remains valid, irrespective of the type of unit system applied. Therefore, conversion factor is not required. For example, Reynolds number remains the same irrespective of the system (cgs or mks).

Comment 1-9. Dimensional equations are not useful over dimensionless equation. True or false. Explain.

The statement is true. Dimensional equations have limited applications and such relationships are empirical. These equations are applied for a specific experimental condition in a particular notation (or system). These have utility in heat transfer process, though empirical, because the process is complex and involves several parameters, i.e. more than 12 parameters.

Chapter 2 : Flow of Fluids

Comment 2-1. What are the differences between gases and fluids?

Most of the gases are compressible when pressure is applied on them. Fluids include those gases which are not compressible or have negligible compressibility. The fluid gases exhibit a behavior similar to that of liquids and hence liquids are also included in the category fluids. Fluid gases are considered as layered. Fluid matter deforms continuously as long as shear stress is applied.

Comment 2-2. Why is fluid pressure difference termed as head and reported in meters (height)?

Normally pressure is reported in the units of pascals or mm Hg. Similarly pressure difference is also measured in the same units. As per the fluid statics principles, the pressure difference is proportional to the height difference of a liquid column. In fluid dynamics also, energy is termed as head. It is easy to measure height of the column of a liquid of a known density, which is numerically equal to pressure energy. The height is termed as head in the discussion of hydraulics.

Comment 2-3. Why is mercury used as a preferred liquid in the manometer?

Mercury is non-corrosive and does not react with the fluid, whose pressure is to be measured. It has low viscosity and can be easily adjusted whenever marginal (minute) pressure changes are observed. Mercury has high density and remains at the bottom of the manometer. It is not volatile.

Comment 2-4. The flow of fluid in the middle of the pipe is faster than the fluid present near to the wall. Why?

A layer of liquid adhering to the pipe wall experiences high resistance to flow. Hence the viscosity of the fluid approaches zero. The fluid layer at the centre of the pipe experiences lower resistance when compared to the resistance offered by the wall-adjacent layers. Thus in the middle of pipe, the flow of fluid is faster.

Comment 2-5. State the relationship between Reynolds number and fluid flow.

The two forces inertial forces and viscous forces influence the fluid flow. Inertial forces diffuse the fluid particles whereas viscous forces make the fluid motion in parallel layers. At low velocities, the inertial forces are less than frictional forces leading to viscous flow of liquid having Reynolds number less than 2100. On the other hand, at high velocities, the inertial forces are more than frictional forces leading to turbulent flow of liquid having Reynolds number more than 4000. The region 2100 to 4000 is known as critical region.

Comment 2-6. Differentiate between constant pressure and constant areas meters.

- Constant pressure meters measure the velocity of the fluid at the orifice compared to the velocity of the fluid in the upstream (pressure is constant). The corresponding decrease is expressed as a pressure head. Example is venture meter.
- Constant area meters measure the difference in the area of the annular space between the plummet and tube. This reflects as a pressure head. Example is rotameter.

Comment 2-7. Why are rate meters frequently used in chemical industries?

Rate meters measure the flow at any instant. In this system, the integrating device gives the reading with respect to time. Such a measurement is essential for automatic adjustment of feed in chemical industries. Rate meters operate by changing the fluid velocity.

Comment 2-8. What is the difference between rate meter and quantity meter?

Rate meter gives the flow at any given instant (point of time). Quantity meter measures the flow of fluid passing through the device over a period of time. This measured reading is divided by the time (taken to record) and reported as quantity.

Comment 2-9. What should be the ideal diameter of the orifice in the measurement of fluid flow?

The hole in the orifice plate is very important to measure the flow. The orifice diameter is about $1/5^{th}$ of the pipe diameter. Then the *vena contracta* (cross sectional area) will be about 0.6th of actual orifice area. In such a situation, the velocity of liquid entering at the orifice can be neglected and the measured reading gives velocity of liquid exactly at the point of the orifice meter.

Comment 2-10. In a rotameter, the term 'float' indicates the lower density of the plummet over the flowing the fluid. True or false. Explain.

The statement is false. The rotameter containing a float is used to measure the flow rate. The upper edge of the float coinciding the etched scale of glass tube indicates the flow rate. The position of float is directly proportional to the flow rate, i.e. higher the position of float, the higher the flow rate. The term 'float' is a misnomer. It doesn't mean that its density is less than the fluid but floats during working. In fact, the float density is more than the fluid, since it is made up of the materials such as lead, aluminum, glass and plastic.

Chapter 3 : Size Reduction

Comment 3-1. Why does size reduction of a powder give polydisperse particles, not monodisperse?

The size reduction of powder always gives polydisperse, because all particles are not uniformly distributed in the chamber to have uniform impact of size reduction. A few particles are present at the corners or edges (near dead spaces), which do not get reduced.

Comment 3-2. Size reduction of a material enhances the action of drugs. Explain.

Size reduction increases powder surface area. When such particles reach the gastric fluid (or intestinal juices), high particle-fluid contact is achieved. As a result, the rate of dissolution increases which in turn promotes rapid drug absorption and further drug action.

Comment 3-3. Size reduction is not possible, if particles do not contain flaws/cracks. True or false. Justify.

The statement is false. Size reduction also generates new flaws/cracks. The solids undergo size reduction when the stress applied exceeds elastic limit. Stress is applied for promoting the flaws or cracks. The nature and number of flaws determine the strength of the particles. If flaws are more in number, then less stress is sufficient for size reduction. Otherwise high level of stress is required to break the particles. Size reduction takes place only after the formation of flaws. Thus particles with no flaws or cracks do not easily undergo size reduction.

Comment 3-4. In a hammer mill, the size of particles is far less than the mesh size of the screen. How is it possible?

In a hammer mill, the hammers rotate at a high speed. The material also rotates at high speed and strikes the high speed hammers. In this process, hammers beat the material into smaller particles, which approach the screen at an angular direction for passing through. The size of the particles must have a smaller size in order to pass the screen in an angular direction.

Comment 3-5. Fluid energy mill is better equipment than hammer mill, for the size reduction of thermo-labile substances. Substantiate.

In a hammer mill, the hammers move at a high speed. As a result, heat is generated during the operation. If the material is heat sensitive, then the material gets degraded during processing. In a fluid energy mill, the moving parts are absent and hence heat is not generated. Though expansion of compressed air is responsible for size reduction, the same process also cools the equipment. Thus, fluid energy mill is suitable for size reduction of thermolabile substances.

Comment 3-6. Why is ball mill not suitable for size reduction of fibrous material?

Fibrous materials are subjected to size reduction by cutting mechanism using sharp blades, i.e. cutter mill is used. Ball mill works by impact and at-

trition mechanisms but not by cutting. Ball mill is suitable for size reduction of hard and abrasive materials, but not for fibrous materials.

Comment 3-7. How is it possible to prevent heat generation in a colloid mill?

During colloid milling, huge amount of heat is generated due to shearing of material between stator and rotor. This leads to increase in the temperature as high as 40 °C. Cold water is circulated around the milling chamber to maintain ambient conditions.

Comment 3-8. Why is it essential to include a screen in the size reduction equipment?

Particles of mono-size or narrow size distribution is ideal for pharmaceutical applications. Size reduction never gives mono-size powder. Hence a screen with desired mesh aperture size is fitted in the size reduction equipment, so that both operations (reduction and separation) occur simultaneously. At the same time, bigger particles further undergo size reduction until desired size is achieved.

Comment 3-9. Size reduction equipment can also be used as mixing equipment. Explain.

During size reduction process, the particles move from one location to another place within the milling chamber. The milling equipment can be used for mixing of the ingredients as randomization is possible. For example, a ball mill without balls can be used as a drum mixer.

Comment 3-10. A single theory is not sufficient to explain milling of all types of the particles. Explain.

Several theories are proposed to explain size reduction process.

- Rittinger's theory proposes that size reduction is directly proportional to the increase in the formation of new surface area. This theory is applicable when brittle and coarse materials are reduced to fines.
- Bond's theory assumes that the energy used in crack propagation and it is proportional to the new crack length formed. It is used for comparing the efficiency of milling operations.
- Kick's theory assumes that the material has flaws distributed throughout its internal structure. Kick's theory is applicable for crushing of large particles.

As particles are available with different structural features, a single theory is not sufficient to explain the milling of all types of particles.

Chapter 4 : Size Separation

Comment 4-1. Why are sieves designated by sieve number rather than (mesh) aperture size?

Sieve number is the number of openings (aperture) present in a linear inch. Sieve number gives an idea about mesh aperture size. Sieve number is a small number (like log partition coefficient) and easy to remember. This is inversely proportional to aperture size. Mesh aperture size is difficult to remember and has no additional advantage. The notation will be remembered by the operators in the production line (while referring to standard operating procedures).

Comment 4-2. What is the difference between nominal size of aperture and nominal diameter of the wire?

Nominal size of aperture and nominal diameter of the wire are two different standards (designations) used in the design of sieves.

- Nominal size of aperture refers to the *aperture* (*size*) through which the particles can pass through. It becomes the size of the sample that has passed.
- Nominal diameter of the wire refers to the *diameter of the wire*, which is used to construct the sieves. If the diameter of the wire increases, the nominal size of aperture decreases and vice versa.

Uniform diameter of the wire is essential in getting reproducible standards of powder with the same nominal mesh aperture size.

Comment 4-3. What is meant by blinding in size separation? How is it prevented?

When particles are placed on the screen, the bigger particles are retained on the screen, while the smaller particles pass through the mesh. The particles having a diameter exactly equal to that of mesh aperture size neither retained nor passed through, but get themselves fit into the screen. This phenomenon is known as *blinding*. It is a serious problem with wet particles. Brushing mechanism is used to overcome the problem of mesh blinding. Alternatively fluidization of the powder prevents blinding of the screens.

Comment 4-4. The sensitivity of the sieve shaker is 50 μm. Explain.

In a sieve shaker, the particles move through the sieves by mechanisms such as tapping, patting, vibration, gyration, etc. The particles pass through the sieves under the influence of gravity. The particles measuring less than 50 μm can't be influenced by gravity and therefore do not pass. Hence sieve shaker has the sensitive of 50 μm particles.

Comment 4-5. Alpine air jet sieve equipment is used for standardization, while industrial equipment is used for the separation of sizes. Justify.

Standardization of powder size is done to know the average particle size and size distribution. A small size of the sample is sufficient. Alpine air jet sieve is used for standardization of powder and equipment only. Size separation is done, when the particles need to be separated into different sizes. This is usually done on large size of the sample using industrial scale equipment.

Comment 4-6. What is the use of two screen-set in Rotex screen?

In the Rotex screen equipment, two screens are used. The top screen has definite aperture size and the bottom screen is having larger aperture size. The top screen determines the size of the particles and the bottom screen has no role except collecting the particles. The two screens hold wooden blocks and rubber balls alternatively. The movement of Rotex screen makes the balls move and hit both the screens and achieve size separation efficiently.

Comment 4-7. In what way air separator is different from sieve shaker?

Air separator separates the particles into two fractions only. One fraction is collected at the bottom which contains bigger particles and the other fraction is collected at the top which contains relatively smaller particles. However, sieve shaker is used to separate the particles into more than two fractions. The number of fractions formed is $n + 1$, where 'n' is the number of sieves/screens used. Particles of smaller size are collected at the bottom, while particles of bigger size are retained on the top.

Comment 4-8. What are the differences between sieving and classification methods in case of size separation?

The differences of sieving and classification methods are given below.

Sieving method	*Classification method*
Different sizes of sieves are used for size separation.	Sieves are not used. It is also known as sorting.
Aperture size is responsible for size separation and for obtaining the desired size.	Density and sedimentation of particles are responsible for the separation of sizes. Heavier particles are collected at the bottom and lighter particles are collected at the top.
Dry powder can be used for separation.	Water medium is used for separation.
Sensitivity of the equipment is low.	Sensitivity is high.
Shaking is important	Velocity of the particles is important.
Accurate particle sizes can be obtained.	Particle size is on range and rough.

Comment 4-9. What are the differences between sedimentation and elutriation methods in the size separation?

The differences of sedimentation and elutriation methods are given below.

Sedimentation method	*Elutriation method*
Gravitation force is acting on the particles to move.	Some particles move against gravitational force.
Feed is supplied from the top.	Feed is supplied from the bottom.

Sedimentation contributes for the separation of particles.	Fluid flow contributes for the separation of particles.
Particles move always in downward direction.	Particles move in upwards also.
Fluid flow is static.	Fluid flow is opposite to the setting of particles.
Separation is based on differences in densities.	Separation is based on differences in densities under the influence fluid flow.
Apparatus is known as separator.	Apparatus is known as columns.
Separation of particle is slow.	Separation of particles is quick.
A stationary medium (water) is used, while particles move.	Water medium moves and particles also move, but in opposite directions.
Equipment is bigger size, often tall.	Apparatus is more compact.

Comment 4-10. Water soluble substances can be separated into different sizes by elutriation method. True or false. Justify.

The statement is false. In elutriation method, a medium is necessary for size separation, which is normally water. If the substance is water soluble, then the solid particles dissolve and size separation has no meaning. In such cases, air is used as medium for size separation.

CHAPTER 5 : Transfer of Heat

Comment 5-1. All metals having good electrical conductivity also will have good thermal conductivity. Explain.

Metals in general are good conductors, i.e., their thermal conductivity values are high compared to nonmetals. The thermal conductivity values are proportional to electrical conductivity, because heat and electricity are conducted by the movement of *electron gas* in a metal.

Comment 5-2. What is the difference between log mean radius and arithmetic mean radius in conduction of heat?

The heat is observed across the solids by conduction. When a circular pipe is evaluated for heat transfer, arithmetic mean radius is expressed. It is easy to apply arithmetic mean rather than logarithmic radius, particularly when a circular pipe is thin. For thick walled tubes, logarithmic mean radius is applied.

Comment 5-3. Dimensional analysis is a useful tool for understanding heat flow of heat. Explain.

Dimensional analysis is a useful tool in understanding the heat transfer. The heat transfer process for convection is more complex. The number of parameters (physical quantities) whose magnitude affects the heat transfer rate is quite large. In such a situation, dimensional analysis is of great help in

optimizing the factors and planning for the experimental conditions. Correlations can be obtained meaningfully at a later period, but dimensional analysis is primarily a useful tool to begin with.

Comment 5-4. In forced convection, the heat transfer is due to molecular diffusion and eddies. True or false. Explain.

The statement is false. In natural convection, heat transfer occurs through molecular diffusion and eddies and is slow and sluggish. In forced convection, the heat transfer occurs by the movement of pockets of warmer fluid, being lesser dense than the ambient fluid. The transfer process is rapid and can be made still higher if pumping (mixing) is taken up.

Comment 5-5. Differentiate between film coefficient and overall heat transfer coefficients.

The overall heat transfer coefficient (U) reflects the capacity of entire transfer of heat of particular fluid. It is obtained by considering two or more film coefficients. The stagnant film coefficient on hot fluid side (h_1), metal wall related coefficients and the stagnant film coefficient on cold side (h_2) are considered for evaluating the overall heat transfer coefficients. Film coefficients are also heat transfer coefficients.

Comment 5-6. Heat transfer is not possible in vacuum. Why?

For heat transfer, the presence of a medium is essential. For example, conduction occurs through a solid body. Convection occurs through moving of hot packets and radiation occurs through electromagnetic waves. Vacuum means lack of electromagnetic waves. Thus heat transfer is not possible in vacuum.

Comment 5-7. Rusted iron rod has increased emissivity than polished iron rod. Explain.

The emissivity of a solid body (material) depends on the surface area and absolute temperature. Apart from these, the nature of metal also influences. The emissivity is sensitive to the state of surface (rough or polished) though the metal remained the same. Rough surface increase the emissivity. The emissivity of a polished iron rod is 0.02 to 0.03 and that of rusted iron rod is 0.6. Polished surface have good reflectivity, i.e. good radiation. In other words, these have low emissivity. All good conducting materials have low emissivity.

Comment 5-8. Differentiate between 'black body' and 'grey body'.

Absorptivity and emissivity are two important parameters applied for defining the nature (properties) of materials.

- A *black body* has a ratio of unity (one), when the ratio of emissivity to absorptivity is evaluated at constant temperature. It radiates the maximum possible energy. Ratio is obtained for a single body and one wavelength is considered.
- A *grey body* has a ratio of constant, when the ratio of emissivity of the body to the emissivity of the black body is evaluated at all wavelengths. Ratio is made using two different bodies and all wavelengths are considered.

The emissivity ratio of black body is one that that of a grey body is less than one.

Comment 5-9. What are the efficient techniques in enhancing the heat transfer in a heat exchanger?

As per the general principles, the heat transfer can be enhanced by increasing the surface area of contact between the hot fluid and cold fluid, which can be achieved by the following.

- Including a large number of tubes (calandria) in the shell-tube heater. Such a shell-tube heater is used in climbing film evaporator and forced circulation evaporator.
- Baffles or pins can be included in the heat transfer equipment. This technique is relatively more efficient than the use of calandria.

Comment 5-10. What is the difference between steam trap and drainage pipe in handling steam?

Steam trap is a device used for minimizing the amount of air and condensate present in a jacket, when steam is used as a heating medium. Air and condensate are moved to a different location, so as to maximize the heating efficiency. A drainage pipe is not effective in removing the condensate and air, particularly steam cannot be escaped.

Chapter 6 : Evaporation

Comment 6-1. Is the evaporation a surface phenomenon or bulk phenomenon? Explain.

Evaporation is a surface phenomenon, since mass transfer takes place from the surface. Such a phenomenon is observed at lower temperature and the evaporation is slow. At higher temperature, boiling of the liquid occurs and practically vapourization is observed even from the bulk (through bubbles). Higher temperature is the operational necessity for evaporation.

Comment 6-2. The objective of the evaporation is to obtain crystals. True or false. Explain.

The statement is false. The purpose of evaporation is to obtain a concentrated liquid by evaporating a large quantity of solvent. When the solution gets concentrated, crystals may be formed simultaneously. But the purpose is not to obtain crystals.

Comment 6-3. What way is drying be different from evaporation?

Evaporation and drying are downstream processes. Normally drying process is attempted after evaporation. The differences are listed in the table below.

Drying	*Evaporation*
Small quantities of liquid are removed from the feed (concentrated liquid).	Large quantities of liquid are removed from the feed.
The end product is largely solid.	The end product is a concentrated liquid.
It is largely a surface phenomenon.	It is a surface phenomenon, but made to be a bulk phenomenon as well.
The operational temperature is a few degrees less than the boiling point of the liquid.	The operational temperature is normally nearer to the boiling point of the liquid.
It is normally a slow process.	It is relatively a rapid process.

Comment 6-4. Evaporation and distillation are similar. True or false. Explain.

The statement is false. Evaporation and distillation are downstream processes. Evaporation is different from distillation as mentioned below.

Evaporation	*Distillation*
Solvent is converted into vapour and allowed to escape. If the solvent is valuable or toxic, then efforts are made to recover or collect the solvent separately.	Liquid is converted into vapour and is condensed and collected, as solvent recovery is also essential.
The product of interest is a concentrated liquid.	It is a separation process. Both separated liquids are important.
It occurs at ambient conditions also.	It occurs at temperature higher than the ambient condition.

Comment 6-5. Heat sensitive products cannot be concentrated by pan evaporator? True or false. Explain.

The statement is True. Heat sensitive products, namely insulin, enzymes, hormones, etc. get degraded when evaporation is carried out in ambient conditions (atmospheric pressure and high temperature). For such products, evaporation is conducted by taking certain precautions, such as evaporation under reduced pressure.

Comment 6-6. Explain the basis for selecting copper and steel, respectively, as materials of construction for kettle and jacket of an evaporating pan?

The purpose of the kettle wall is to effectively transfer the heat. The function of jacket is to prevent the loss of heat. Thus kettle should be made with a good conductor and jacket material must be poor conductor of heat. Copper has good thermal conductivity and is used as a material of construction of the kettle. Comparatively steel has lesser thermal conductivity and is used to construct jacket.

Comment 6-7. What is the modification done in the heating compartment to increase the rate of evaporation?

Rate of evaporation is directly proportional to the surface area of contact for heat transfer. The surface area can be increased by incorporating more number of tubes in the calandria, which occupies limited space. Thus it is possible to increase the rate of evaporation.

Comment 6-8. What is the function of a deflector in an evaporator of climbing film/forced circulation type?

In a climbing film/forced circulation type of evaporator, vapour gets entrained with the liquid. As a result, more foam (a blend of vapour and liquid) is formed during evaporation. Foam is a serious problem and is prevented by arranging a deflector at the top portion above the heating tubes. The foam gets broken, vapour escapes from the top, while the liquid is collected at the bottom.

Comment 6-9. Climbing film evaporator is suitable for high viscosity liquids? True or false. Explain.

The statement is false. Falling film evaporator is preferred. In the climbing film evaporator, the mechanism involves the formation of a film and its raising during evaporation. If the liquid becomes viscous (after evaporation) it cannot be climbed easily. Therefore, falling film evaporation is preferred, wherein gravitational force assists the flow of high viscosity liquid and hastens the process of evaporation.

Comment 6-10. The economy of multiple-effect evaporator is higher than that of the single-effect evaporator. Justify.

The economy of evaporator depends on the total mass of vapour formed (related to the mass of concentrated liquid obtained) for a given mass of steam supplied.

In single effect evaporator, concentrated liquid is collected from the 1st evaporator (one unit), when one unit of steam is supplied to 1st (one) evaporator.

In a triple effect evaporator, the concentrated liquid is collected from all the three evaporators, while one unit of steam is supplied to the 1st evaporator. Economy is possible because the vapour of 1st evaporator is introduced as a heating medium into the 2nd evaporator. Similarly, the vapour head of 2nd evaporator is connected to the heating element of the 3rd evaporator. This process continues (series connection).

Hence multiple-effect evaporator is always more economical than that of the single-effect evaporator.

Chapter 7 : Distillation

Comment 7-1. Is the distillation a separation process or an extraction process? Explain.

Distillation is a separation operation and not an extraction operation. Distillation is used to separate volatile components from non-volatile/less volatile components. Separation may also be considered as a purification process. Distillation is a concentration process of active constituents. In extraction, solvent action is necessary and often refluxed with solvent and not distilled. Extraction may also be a separation process, but operationally the product is obtained from a feed of solid/liquid.

Comment 7-2. Is the Dalton's law applicable in the distillation process? Explain.

Yes, Dalton's law states that the total vapour pressure of the liquids blend is equal to the sum of the partial pressures of individual liquids (A and B) present in a solution ($p_m = p_A + p_B$). If the total pressure of the solution (p_m) is equal to the atmospheric pressure then only the liquid gets distilled. Therefore, Dalton's law is applicable to distillation.

Comment 7-3. What is the importance of the Florentine receiver?

Florentine receiver is a tall cylindrical flask having two outlets on its wall; one at the bottom for collecting the high-density liquid and another at the top for collecting the low-density liquid. Whenever a distillate is expected to contain two immiscible liquids, the condensate is collected into the Florentine receiver. During the distillation, the mixture condenses and gets separated into two layers (in the Florentine receiver) based on their densities. Then Florentine receiver permits the collection of separate layers.

Comment 7-4. What are the precautions taken while assembling the apparatus for simple distillation?

Distillation flask is connected to a side-arm bend, which is sloping downwards and in turn attached to a condenser. Thermometer (through a cork) is placed in such a way that the thermometer bulb should be just below the bend of the side-arm. The flask should be either half-filled or two-third filled with the feed. A few pieces of porcelain chips are placed in the flask to avoid bumping.

Comment 7-5. Azeotropic distillation is used to separate individual components into pure state. True or false. Explain.

The statement is false. An azeotropic solution or constant boiling solution is one which distills unchanged at a constant temperature. The composition of the liquids and in the vapour state remains the same. Therefore the solution (behaves like a pure liquid) distils without change in composition.

Hence such a solution (binary mixture) cannot be distilled into pure components. Azeotropic distillation is used for the separation, but the separated parts are: one pure component and another is again an azeotropic solution.

Comment 7-6. Should the distillation be carried out at atmospheric pressure or can it be carried out at altered pressure?

Distillation is normally carried out at atmospheric pressure. Examples are simple distillation, steam distillation and azeotropic distillation. In special cases, pressure can be altered. Accordingly, the boiling point of the solution is also altered (normally decreases). Vacuum distillation, molecular distillation and flash distillation are carried out at low pressure (vacuum).

Comment 7-7. Suggest the methods to avoid foaming during vacuum distillation?

Foaming is a common problem during vacuum distillation, if the solution contains even traces of saponins. Addition of capryl alcohol to the liquid (to be distilled) prevents the problem. Alternatively a capillary tube is inserted along with a thermometer into the neck (cork) of a Claisen flask. The stream of air is drawn in breaks the rising foam.

Comment 7-8. Vacuum distillation is suitable for the purification of vitamins. True or false. Explain.

The statement is true. Vacuum distillation is used for the purification of vitamins. Vitamins undergo oxidation (degradation) at its boiling temperature in a simple distillation. On applying vacuum, the boiling point of the solution is lowered and the solution gets distilled at a lower temperature. Thus vitamins are protected against oxidation. Hence, it would be ideal to apply vacuum to the distillation.

Comment 7-9. For a substance with high molecular weight and low volatility, steam distillation is a better separation technique. True or false, Justify.

The statement is true. A substance with a high molecular weight normally boils at a high temperature. At such a high temperature, the active principles may degrade. Hence, normal distillation is not suitable. The substances having high molecular weights are not miscible with water. Steam distillation would be preferred. A mixture of immiscible liquids begins to boil, when the sum of their vapour pressures is equal to the atmospheric pressure. The solution boils at a temperature below the boiling point of the lower boiling liquid (i.e. water).

Comment 7-10. There is no relationship between mean free path and the assembly of apparatus for molecular distillation? True or false. Justify.

The statement is false. The *mean free path* is the distance travelled by the molecules of high boiling point liquids without any collision. If the vapour molecules collide with one another, they become liquid and reach moth-

er liquor, rather than reaching the condenser and receiver. In vacuum, the mean free path will be slightly longer. The condenser is kept close to the evaporating surface (less than the distance of mean free path), so that the vapour molecules travel (without collisions), reach the condenser, get condensed and collected in the receiver. Therefore, the knowledge of mean free path is essential, while assembling the apparatus for molecular distillation.

Chapter 8 : Drying

Comment 8-1. Drying of solids prevent deterioration of drugs. Justify.

Drying is attempted to remove water (or solvent) from the solids. Presence of water in the products causes degradation by either chemical or microbial means and often causes physical instability. In the absence of water, the stability of the products increases. Examples are blood products, skin, tissues, etc. The products include animal or plant origin. Therefore, drying of solids is attempted to remove water and to increase the product shelf life.

Comment 8-2. How is desorption different from sorption?

Desorption means *removal* of water (vapour or solvent). *Sorption* means *absorption* of water (vapour or solvent). Sorption/desorption depends on the nature of material and moisture content in the ambient conditions.

- If the ambience contains more moisture than the equilibrium moisture content (EMC) of a solid, sorption takes place. This process continues until equilibrium is attained.
- If the solid contains higher moisture content than the EMC and the environment has low moisture, then desorption takes place. This process continues until equilibrium is attained.

Hence drying of solids is controlled by adopting favourable conditions.

Comment 8-3. How is the ending of first falling drying rate period identified?

During the drying, the following steps are identified.

- Water moves towards the surface by capillary action, if sufficient water is present in the solid.
- After removal of maximum water content, capillary network would be broken and the remaining water can't move.
- On further exposure to the hot air, the solid exhibits an increase in temperature. Then water present inside the solid absorbs heat energy and gets converted into vapour. Energy of vapour increases with the increase in the temperature. After attaining sufficient heat energy, water vapour breaks the solid and escapes from the surface leading to the formation of cracks. Appearance of first crack indicates the ending of first falling drying rate period or beginning of second falling drying rate period.

- Further exposure of heat allows the substance to attain equilibrium moisture content (EMC).

Comment 8-4. EMC values of all the substances remain same. True or false. Explain.

The statement is false. Different substances have different EMC values. For example starch (hydrophilic) has 19 %, whereas ethylcellulose (hydrophobic) has 7 %, given the ambient temperature. Talc has zero EMC and that of sand is also zero. *Equilibrium moisture content* (EMC) is the water present in the sample whose vapour pressure is equal to the vapour pressure of the atmosphere. EMC depends on the nature of the material and temperature of the ambient air. The EMC values of non-porous solid are low and that of the porous solids is relatively higher.

Comment 8-5. Arrange the dryers in the ascending order of drying times taken for a given material: drum dryer, tray dryer, spray dryer, fluid bed dryer, freeze dryer. Explain.

The ascending order of dryers as per drying times is: spray dryer > drum dryer > fluid bed dryer > tray dryer > freeze dryer. Drying is very rapid in spray dryer as it requires 3 to 30 sec to complete drying. Drum dryers requires 6-15 sec, while fluid bed dryer takes 20-40 min to complete one cycle of drying. Tray dryer requires 5-6 h. Freeze drying is very slow and involves several steps. Thus, it requires about 10-20 h for drying. However, the time required for drying depends on the mechanism of drying and amount of water present in the sample.

Comment 8-6. Drying rate is lesser in a static bed dryer compared to a moving bed dryer. True or false. Explain.

The statement is false. When hot air is continuously passed over the surface of a solid bed (static), drying takes place only from the surface. For example, drying rate is low in tray dryer and drying time is high (5-6 h). In case of moving bed dryers (e.g. fluid bed dryer), each and every particle present in the bulk is under motion and exposed to the dry air. Therefore, drying rate is high and drying time is low (20 to 40 min) in a moving bed dryer.

Comment 8-7. Tray dryer can be used for drying of thermolabile products. True or false. Explain.

The statement is false. Tray dyer operates at ambient conditions (atmospheric pressure). In a static-bed dryer, drying takes longer time, i.e. 5 to 6 h. If the product is thermolabile, degradation is possible in a tray dryer. Spray dryer or freeze dryer is preferred for thermolabile products.

Chapter 9 : Mixing

Comment 9-1. Differentiate mixing and agitation.

The two terms, mixing and agitation, are used synonymously, though some differences exist scientifically.

- *Mixing* is a process in which particles of two or more substances are randomized.
- *Agitation* is a process in which the dissimilar particles are allowed to move in zig-zag directions resulting in a uniform mix.

The other terms used to represent similar operation are: blending, trituration, tumbling, etc.

Comment 9-2. What is the ideal proportion of powders chosen for effective mixing?

Ideally, equal quantities of different powders are taken for mixing, which may not be always possible. If a material is present in lower amounts than the other, then geometric dilution method should be applied for mixing.

Comment 9-3. Write the differences in the sampling methods of powders: scoop sampling and thief probing.

The sampling methods differ as given below.

Parameter	*Scoop sampling*	*Thief sampling*
Procedure	The powder sample is drawn from the surface only and not from the middle and bottom portions.	The powder sample is drawn from surface as well as from inside portions.
Disadvantage	The bulk of the material may get segregated during collection and packing. Hence, the sample represents a segregated sample.	During the insertion of the probe, some degree of compaction may take place. Some material from surface may go inside along with the probe.

Comment 9-4. Write the relationship between the efficiency of mixing and the volume of the material filled in the mixer.

The mixing bowl should not be filled with powder completely (100 %). The powder-bed normally expands during the three-directional movement (i.e. mixing). Therefore, sufficient space should be allowed, so as to allow effective mixing. Normally 60 to 75 % fill volume is attempted.

Comment 9-5. Dead spots are objectionable in a blender. True or false. Explain.

The statement is true. Dead spots are the areas wherein the material (either solid or liquid) remains unmixed. Such areas are observed in a ribbon blender. Unmixed material if enters into the product, problem of non-uniformity occurs. Dead spots are formed due to wrong engineering of the equipment, i.e. mixing element does not reach the entire volume of the bowl. Planetary mixer is free from dead spots, because the appearance is curved and do not have sharp edges.

Comment 9-6. Can one equipment be used for the mixing of different types of materials?

Yes. Sigma blade mixer and planetary mixer are used for the semisolids mixing as well as solid-solid mixing. For solid-solid mixing, minimum energy is required, whereas mixing of semisolids requires more energy. The same equipment works at different energy levels, depending on the nature of materials.

Comment 9-7. Fluidized air is used for conveying, drying and size reduction. Can it be used in mixing of powders? Explain.

Yes. Fluidized air is allowed to enter from the bottom of the stationary container. The fluidized air allows the solid bed to expand initially and facilitates the movement of the particles to tumbling action. Thus fluidization also promotes mixing. In fact, fluidized bed equipment can be used for conveying, mixing, coating and drying.

Comment 9-8. The nature of miscibility of liquids is known for selecting the mixing equipment. True or false. Justify.

The statement is true. Liquid-liquid systems are classified as:

1. Easily miscible liquids in all proportions (e.g. ethanol and water). Mixing of these liquids is easy and requires simple devices.
2. Partially miscible liquids (e.g. cresol and water). Mixing of partially miscible liquids requires vigorous mixing equipment.
3. Totally immiscible liquid system (e.g. turpentine oil and water). Mixing of immiscible liquids is difficult and is achieved by the use of heavy duty (efficient) homogenizers.

Liquid formulations consist of solid mixing and liquid combinations. Therefore, the knowledge of miscibility of the liquids gives an idea about the selection of right equipment.

Comment 9-9. Explain the differences among the movements, radial, axial and tangential.

The type of movement induced during mixing depends on the type of impeller.

- Radial movement leads to movement of the liquid from the centre to the periphery and vice versa.
- Axial movement means up and down movement of the liquid, which is also called longitudinal movement.
- Tangential movement means circular movement of the liquid.

Comment 9-10. Pipe mixers are used for mixing operation only. True or false. Explain.

The statement is false. Pipes are used to convey the liquids from one location to another location in an industry. Pipes are modified by introducing the baffles in the interior of the pipe. Presence of baffles increases agitation of the liquids resulting in mixing while conveying. Hence mixing and conveying processes of the liquids can be achieved simultaneously thereby saving time and money.

Chapter 10 : Filtration

Comment 10-1. Clarification is faster for given nature of feed. Explain.

Clarification is a faster process, because the feed contains low amount of solids (1 % w/v). The resistance offered by the filter cake is low. In case of slimy feed, filter aids are added before proceeding for separation. Even then the rate of filtration is faster. If the solid content in a slurry is high (>5 %), then ordinary filtration takes long time. The resistance offered by the filter cake is high.

Comment 10-2. What are the factors related to the feed relevant for the filtration?

The characteristics of feed influence the selection of a filtration equipment. The amount of solids present (high/low) and particle size (5 μm or above) are of the primary concerns. Particle size distribution influences the porosity of the filter cake. These decide the thickness of the filter cake. The nature of slurry (sliminess) influences the resistance (pressure drop) across the filter cake. Apart from these, viscosity of the liquid also influences (inversely proportional) the rate of filtration.

Comment 10-3. What are the differences between pressure filtration and vacuum filtration?

Both the methods are used to increase the rate of filtration. However differences are present as given below.

Pressure filtration	*Vacuum filtration*
It involves application of positive pressure on the filter medium.	It involves application of negative pressure below the filter medium.
It can be created by pumping the liquid on to the filter medium using a pump such as centrifugal pump.	It can be done by creating negative pressure (vacuum) using a vacuum pump.
It increases the pressure on the equipment leading to the occasional problem of bursting of the equipment.	The negative pressure decreases the load leading to occasional problem of collapse of equipment.
Bursting of the equipment is more dangerous.	Collapse of the equipment is safer.
It may increase the boiling point of the liquid.	Negative pressure decreases the boiling point of the liquid, which may sometimes lead to evaporation of the solvent.
Pressure filtration is relatively difficult to handle.	Vacuum filtration is easy to handle.

Comment 10-4. Why coagulants are added to the slurry before proceeding for filtration?

Colloidal (or mucilaginous) materials if present in the feed, the filter medium may get clogged. Then filtration becomes difficult (very slow or even stops). Coagulants (ferrous sulphate or aluminum sulphate) are substances that react with the colloidal materials and produce aggregates (or solids) with bigger size, which can be easily filtered. If the mucilaginous material deposits on the medium (as in sand filter), backwashing or reusing the filter medium becomes a cumbersome procedure.

Comment 10-5. Filter aids increase the rate of filtration by many times compared to the filter medium. Explain.

Filter aids (solids) deposit on the surface of the filter medium and prevent the plugging of the pores/perforation. In general, filter medium initially offers low resistance, but the resistance increases gradually as the filtration continues. This is possible due to clogging of filter medium or impervious filter cake. The filter aids act on the following ways: preventing the plugging of the filter medium, providing porous filter cake and floating in the fluid (present on the medium). Thus, resistance decreases and flow rate increases several folds with the help of filter aids.

Comment 10-6. Is there any relevance of the amount of filter aids used in filtration? Explain.

Yes. The amount of filter aid used for filtration is critical for achieving the efficient filtration. At low amounts, filter aid supports the thickness of the filter cake resulting in increase in resistance of the filter cake. As the amount of filter aid is increased, rate of filtration increases. Beyond a certain amount of filter aid, the thickness of the filter cake increases without affecting the cake porosity. Beyond a particular amount, filter aids do not produce any additional benefit.

Comment 10-7. What is meant by washing of the cake? When is it essential?

During filtration, the solids (filter cake) deposit on the filter medium. Due to the porosity of the cake, the solvent may get entrapped by the cake. When the cake is a desired product (as in case bulk drug production), then it should be made free from the solvent for the next step of filtration. The process of removing the solvent from the cake is called washing of the cake. It can be done either by passing the water through the cake (as in case of filter press) or back flushing (as in case of filter leaf and meta filter).

Comment 10-8. Is it possible to obtain the sterile liquid by filtration? Explain.

Sterile liquid is the one which is free from bacteria and also free from all the foreign particles. Sterile liquid can be obtained using membrane filters (officially approved by USFDA) having pore size of 0.2 or 0.45 μm, Sterile filtration is also possible using meta filter, as all parts of the meta filter are made up of metal, which can be sterilized. In fact, sterile filtration is one of the choices for heat sensitive products (e.g. ascorbic acid injection), which cannot be autoclaved. In addition, filtration removes foreign particles.

Comment 10-9. Vacuum filtration is suitable for sterile preparation. True or false. Justify.

The statement is false. Sterile filtrations should *always* be carried out by a pressure filtration technique only, not by vacuum filtration. In vacuum filtration, there is a possibility of drawing bacteria into the receiver from the leaky joints, leading to contamination of the product.

Comment 10-10. If the slurry contains 25 % solids or more, what is the type of filtration equipment employed? Why?

A slurry containing 25 % w/v or more solids is not considered as clarification. Hence filtration equipment is employed capable of separating high amount of solids has to be performed. Drum filter or frame-and-plate filter press is capable of filtering large amount of suspension. These two equipment function on the mechanism of surface filtration.

Chapter 11 : Centrifugation

Comment 11-1. What is the relationship between sedimentation force and centrifugal force?

A slurry containing solids (dispersed or suspended) can be separated from the liquid based on differences in the densities and relative terminal velocity of solid particles. In case of sedimentation, gravitation force acts on the particles. The sedimentation (separation of solid) is difficult to achieve for the following reasons.

- The differences in the densities between two liquids are low, as in emulsions.
- The particle size is low (< 5 μm) so that particles move by Brownian motion, as in colloidal dispersions.

In the above cases, the gravitation force is replaced by centrifugal force. The speed of the centrifuge becomes the deciding factor for separation. Centrifugal effect is several times higher than the gravitational force, i.e. as high as 104 or 10,000 times higher than the gravitational force (9.807 m/s^2).

Comment 11-2. Physical stability of the emulsion can be evaluated with the aid of centrifugation. True or false. Justify

The statement is true. In general, creaming (separation process) is a slow process. The separation of the two phases (of an emulsion) can be increased by inducing stress in a centrifuge. A stable emulsion should not show any signs of separation even after centrifuging at 2000-3000 rpm at room temperature. Similarly, the study can be extended to suspensions also.

Comment 11-3. What is the use of centrifuge in bioequivalence studies?

Bioequivalence studies are carried out to compare the equivalence of a test dosage form with an innovator's product. This can be tested by determining the amount of drug present in the blood (or urine). Drug is present in the blood (or urine) in the form of colloidal dispersion and separation of drug can be achieved using a centrifuge.

Comment 11-4. Suggest a centrifuge which can give high centrifugal effect.

From the theory of centrifugation, the two factors are identified.

- Centrifugal effect is directly proportional to the diameter of the particle. If the size of the particles in the slurry is small, then high centrifugal effect is necessary to separate them.
- The smaller the size of the centrifuge, the higher the speed (rpm). Centrifugal effect is proportional to the square of the speed. Further small size is preferred, because high amount of stress is applied on the tubes.

Comment 11-5. How is sedimentation centrifugation different from filtration centrifugation?

Sedimentation and filtration are the processes employed for separation of the solids in the slurry. When both are slow processes, centrifugal force is applied for quick separation.

Sedimentation centrifugation	*Filtration centrifugation*
Separation of solids from slurry is achieved by settling.	Separation of solids from slurry is achieved by passing the slurry through a porous medium.
Densities of the solid and slurry decide the extent of separation.	Densities of solids and slurry do not influence. Particle size and pore size of filter medium govern the separation.

Comment 11-6. Filtration centrifuge is a modification of filtration equipment. True or false. Justify.

The statement is true. Filtration centrifuge consists of a vessel in which perforations are present. During operation, the material is thrown through the perforations by centrifugal force. But due to the presence of perforations, the solid particles are retained on the perforated plate, allowing the liquid to pass through. Hence both 'centrifugation' and 'filtration' mechanisms works in filtration centrifuge. In other words, it is a '*fast working filter*'.

Comment 11-7. What is the major limitation of a filtration centrifuge over filter?

In a filtration centrifuge, separation of solids takes place by passing through the filter medium (perforated plate) with the aid of centrifugation. Hence, compact cake is formed with low porosity and high density. It is practically difficult to remove the cake. Special measures must be taken, during centrifugation to remove the cake, as and when it is required.

Comment 11-8. Centrifugal separation is a batch process. True of false. Justify.

The statement is false. Most of the cases, the centrifuges work at high rpm and the bowl is under constant motion. The entry of feed and the collection of separated solid (or liquid) are difficult to achieve on a continuous basis. However, equipment (supercentrifuge –for immiscible liquid as in emulsion, conical disc centrifuge or horizontal continuous centrifuge for solid separation) are available for a continuous separation. Even in these cases, construction and design are complicated.

Comment 11-9. How can the centrifugal effect be effectively applied for separation?

Centrifugal effect can be effectively applied by selecting a centrifuge having either by big diameter vessel or process the material at high speed (rpm). Since centrifugal effect is directly proportional to the square of the rpm, it is appropriate to select a centrifuge of the same size and can be made to operate at higher rpm.

Comment 11-10. Suggest a centrifuge when a large volume of material needs to be handled?

Centrifuges are available in wide range of designs and capacities and therefore the selection of the centrifuge has become important. When large volume of feed need has to be processed, a centrifuge of big size is preferred, provided low centrifugal effect is adequate. A centrifuge with high rpm cannot be operated easily, because of the induction of high stress.

Chapter 12 : Materials of Construction

Comment 12-1. Why is stainless steel used instead of steel (iron) for the fabrication of equipment?

Steel (iron) is available with carbon and is also known as cast iron and carbon steel. These materials are hard, brittle, easily attacked by acids and have low thermal conductivity. Such properties are the limitations in the design of equipment. These are improved by adding other metals. Nickel improves toughness, chromium increases hardness and makes the metal abrasive resistant and titanium (nobium) stabilizes the alloy. Thus stainless steel, an alloy of iron, was used for fabrication of manufacturing equipment.

Comment 12-2. Austenitic steel is frequently used for the fabrication the equipment. Why?

Austenitic stainless steel is an alloy of carbon, chromium and nickel along with steel. These metals enhance the properties of stainless steel, which is used for the fabrication of equipment. It is non-magnetic.

- Chromium enhances the resistance to corrosion. Chromium has great affinity to oxygen and forms a film of chromium oxide (at a molecular level) on the surface of the steel. During usage, this film may wear off, but the alloy has the capacity to self repair, i.e. the film will be formed again. Thus, austenitic steel have longer life of equipment.
- Nickel prevents aqueous corrosion. When nickel and chromium is added to stainless steel in sufficient amounts, the crystal structure changes.

Austenitic steel is not be hardened by heat treatment.

Comment 12-3. High coefficient of thermal expansion of metal is not necessary for the metal used in designing the equipment. True or false. Justify.

The statement is true. High coefficient of thermal expansion of the metal causes complications in designing the equipment. Usually high stress conditions like heating, steaming, high degree of mixing, etc. are used during chemical reactions. These situations may crack the metal and spoil the purpose of reaction. Hence the material should be able to maintain size and shape of equipment at working temperatures. Stainless steel is a suitable metal for the construction of equipment.

Comment 12-4. Why are noble metals not used for the construction of equipment?

Noble metals are gold and silver. Both have the necessary qualities (corrosive resistance, ease of fabrication, etc.). These are expensive and hence are not used for the construction of equipment.

Comment 12-5. In what way type II glass containers are different from remaining glass containers?

Apart from silica, glass containers contain alkali substances to make the containers suitable for different purposes. But alkali present in the glass composition may get leached out during storage. Type II glass containers are treated with sulphur dioxide vapour to neutralize alkali present on the surface of the glass. Therefore, they undergo lesser leaching when compared with other glasses. Water attack test (whole glass containers test) is conducted to test their leaching ability.

Comment 12-6. Nonmetals are preferred for the construction of equipment over metals. Explain.

In general nonmetals are preferred, because these do not undergo corrosion, while most of the metals corrode. Further, nonmetals contribute to the

economy, ease of fabrication and performance. But mechanical strength of nonmetals is weak. Hence wherever necessary, at least nonmetal coating are applied on metal surfaces.

Comment 12-7. Why is hardening of rubber necessary?

The naturally occurring rubber is known as soft rubber. It has excellent resistant properties against dilute mineral acids, alkalis and salts. It is easily attacked by oxidizing media, oils and organic solvents. Rubber lacks the necessary mechanical strength. Hardening of rubber is made by processing (vulcanization, crosslinking with sulphur) or adding carbon black, so that the rubber exhibits adequate mechanical strength.

Comment 12-8. What is the material used for the preparation of dropper assemblies of eye drops and why?

Neoprene (polychloroprene) rubber is used for the preparation of dropper assemblies of eye drops. Sterility is an important requirement of eye drops and neoprene rubber is preferred as it can be sterilized using an autoclave.

Comment 12-9. What is the desirable property for the stoppers used for freeze dried products?

Freeze dried products are highly hygroscopic in nature. Therefore, they should be stored in well closed containers, which are resistant to water vapour permeability. Glass containers with closures made up of butyl rubber serve the purpose.

Comment 12-10. Differentiate thermoplastics from thermosetting plastics.

The differences of thermoplastics and thermosetting plastics are given below.

Thermoplastics	*Thermosetting plastics*
A plastic material can be softened repeatedly by heating and can be moulded into different shapes again and again.	A plastic material once set, it does not become soft on heating and cannot be moulded a second time.
These are flexible and can be bent easily without breaking.	These are not flexible, i.e. hard and rigid.
These are also known as 'thermosoftening' plastics.	These are also known as 'thermosets'.
Examples: polyethene and PVC.	Examples: Bakelite and melamine.

Chapter 13 : Corrosion

Comment 13-1. What is the relationship between corrosion and metals in electrochemical series?

Corrosion is involved on metal surface due to adverse environmental conditions (oxygen, acid, etc.). Corrosion involves the movement of electrons, i.e. oxidation and reduction reactions. The relative reactivity of a metal can be identified by considering the position of metal in the electrochemical series. The metal selected from the top of electrochemical series acts as cathode and from the bottom of the series is known as anodes. For example, top metal Cu^{+2}/Cu acts as cathode and Zn^{+2}/Zn acts as cathode, when standard reduction potentials of electrodes are considered.

Comment 13-2. For corrosion to occur, at least two different metal surfaces are required. True of false. Explain.

The statement is false. Corrosion is an electrochemical reaction during which anode and cathode areas are developed. If two different metal surfaces exist together, corrosion becomes faster. This corrosion on two-metals is known as galvanic corrosion. However, corrosion is also possible to occur on the same metal, but at different locations (anodic and cathodic areas). These promote the corrosion. Example is iron metal in hydrochloric acid solution.

Comment 13-3. In a solution, two dissimilar metals should not be allowed to come in contact with each other. Why?

Two dissimilar metals mean metals having different standard electrode potentials. In other words, while one metal acts as an anode, and the other metal acts as cathode. When these two metals are connected, transfer of electron takes place, i.e. oxidation-reduction reaction. Thus corrosion occurs at the points of contact and is known as galvanic corrosion. For this reason, such metals are not allowed to be in contact with each other for preventing corrosion.

Comment 13-4. Rusting of iron is quicker in saline water than in ordinary water. Why?

Rusting of iron normally occurs in ordinary water, but to a lesser extent, because fresh water contains fewer dissociated ions (H_3O^+ and OH^-). Salt water promotes rusting by two ways.

- In salt water, sodium chloride (strong electrolyte) dissociates completely into ions.
- Active ions (Na^+ and Cl^-) become the centers of corrosion. Salts create cells on the metal surface.
- Medium permits the electron transfer.

Thus corrosion of iron is higher in salt water.

Comment 13-5. Corrosion is often more rapid at the places where some corrosion is already taken place. Why?

On the metal surface, the electrolyte solution is partially confined (e.g. deep crevice or laying surface) at a particular location. This promotes the

corrosion. Once an area is confined with corrosion (as in case of oxygen concentration corrosion), the same area further gets corroded more rapidly than the other part of surface (of the metal). This happens because the oxygen content is reduced at the confined electrolyte and this triggers the adjacent metal to become anodic. This happens in preference to the new surface at a different location.

Comment 13-6. Aluminum corrodes faster than iron, even though iron is placed below aluminum in the electrochemical series. Why?

Aluminum corrodes at a faster rate. In this process, aluminum oxide films are formed which is held tightly to the metal surface. The oxide film prevents further corrosion of aluminum. Iron corrodes slowly and the formation of iron oxide film is slow. This film does not prevent the iron from further corrosion. Thus corrosion of iron is a continuous process.

Comment 13-7. Why is corrosion high in acidic medium than alkaline medium?

The acidic medium contains H^+ ions, and these strongly influence the corrosion. The metal gets dissolved in acid, e.g. iron. The H^+ ions have tendency to take up electrons to form H_2 gas. H^+ ions promote anodic corrosion.

Comment 13-8. Why is brass a preferred alloy for the construction of equipment?

For the construction of equipment, the mechanical strength of the metal is a primary factor, secondly the metal should be resistant to corrosion. Copper act as cathode and react in the following ways.

- Copper forms copper oxide film on the surface of the equipment, which makes the vessel corrosion resistant.
- Copper oxide film is soluble in most acids and hence copper is not a suitable material for construction.
- Corrosion further leads to loss of mechanical strength.
- Copper can also react with the components in the formulation, which is again not desirable.

When zinc is added to copper, the alloy is known as brass, which has high corrosion resistance and also improves the mechanical strength. Thus, the limitations can be overcome.

Comment 13-9. A piece of pure zinc and impure zinc are placed in a salt solution, which will corrode faster. Why?

Impure metals in general corrode faster. Purity and physical state (smooth or surface imperfections) are also relevant. The differences are shown in the table below.

Pure zinc	*Impure zinc*
Pure zinc metal has the standard electrode potential of –0.763 volts. Since, it is a single metal, it is difficult to form an electrochemical cell (anode and cathode). Zinc exhibits low corrosion in the presence of acid.	Impure zinc contains a second metal say copper along with zinc. These two metals have different standard electrode potentials (copper being high +0.337 volts). Copper is placed above zinc in the electrochemical series. The presence of two metals can form tiny electrical cells. Under the influence of adverse environment, anode area gets corroded rapidly.

Comment 13-10. Highlight two non-metal linings on the material for the construction of equipment.

The frequently used nonmetals in pharmacy are tin, glass and organic substances.

- Tin coated steel is known as tinplate and is used for the fabrication of containers meant for food products.
- Glass lined steel (by cladding) equipment is used for handling corrosive chemical reaction applications leading to the production of drugs and intermediates.

Chapter 14 : Transportation of Solids

Comment 14-1. Why should improper handling of materials be avoided?

Improper handling causes the damage or loss of material. Further improper handling leads to:

- Production delays
- Loss of machine time and operational time
- Increase in inventories

Such damage may lead to employee frustration and reduce morale, due to constant production delays.

Comment 14-2. Idlers are the essential components of a belt conveyor. Explain.

Idlers support the belt for conveying the solids.

- Troughing idlers placed beneath the upper part of the belt help in holding more material on the belt till the belt reaches the delivery end.
- Non-troughing idlers placed beneath the lower part of the belt help in supporting the belt till the belt reaches the pulley on feeding side.
- Snubbers idlers pushes the belt towards drive pulley to increase the contact between belt and pulley for continuous and smooth running.

Comment 14-3. Belt conveyor is suitable for transporting materials when the path of travel involves many turns and lifts. True or false. Justify.

The statement is false. A single belt system is not suitable.

- Two separate individual belt systems are necessary for each straight line. Then material from one belt is allowed to fall on another. This arrangement is cumbersome and handling is difficult.
- Pneumatic conveyor is suitable for transporting material when the path involves many turns and lifts. In the pneumatic conveyor, high velocity air is made to pass through a bed of solid particles. The solid particles are dragged and suspended by the air. Such a fluidized bed can transport particles in any direction.

Comment 14-4. What are the special features that make a screw conveyor necessary in the pharmaceutical industry?

Screw conveyor is the only conveyor that can transport the material either horizontally, vertically or inclined. It is a conveyor in which mixing, de-watering, heating, and cooling facilities are available. Transport of solids is possible under closed conditions. These make the screw conveyor as an important equipment in the pharmaceutical industry.

Comment 14-5. What is the difference between the bins and silos?

A bin is a fairly wide and not so tall. It is cylindrical or rectangular vessel. A silo is a tall and relatively small in diameter. Both are used for the storage of solid materials.

APPENDIX-II

Key to MCQs

Chapter 1. Industrial Processing and Basic Principles

1. D	2. B	3. A	4. C	5. B	6. B	7. D
8. C	9. B	10. D				

Chapter 2. Flow of Fluids

1. C	2. A	3. B	4. C	5. C	6. D	7. D
8. A	9. A	10. C	11. D	12. C	13. C	14. B
15. A	16. C	17. A	18. D	19. C	20. A	21. B
22. C	23. C	24. A	25. C	26. A	27. B	28. B
29. C	30. B	31. B.				

Chapter 3. Size Reduction

1. A	2. A	3. A	4. A	5. D	6. A	7. C
8. D	9. D	10. D	11. A	12. B	13. D	14. B
15. D	16. D	17. A	18. D	19. C	20. D	21. D
22. C	23. B	24. C	25. D	26. C	27. B	28. A

Chapter 4. Size Separation

1. D	2. D	3. A	4. B	5. D	6. A	7. D
8. C	9. A	10. D	11. A	12. C	13. D	14. D
15. A	16. D	17. B	18. B	19. D	20. B	21. B

Chapter 5. Flow of Heat

1. A	2. C	3. C	4. A	5. A	6. A	7. A
8. D	9. D	10. C	11. A	12. D	13. D	14. B
15. C	16. C	17. C	18. C	19. C	20. D	21. A
22. A	23. A	24. A	25. B	26. B	27. D	28. C

29. C	30. D	31. C	32. C	33. C	34. B	35. C
36. B	37. B	38. D	39. A	40. B		

Chapter 6. Evaporation

1. D	2. C	3. B	4. D	5. B	6. D	7. D
8. C	9. C	10. A	11. A	12. C	13. A	14. D
15. B	16. D	17. A	18. D	19. B	20. A	21. B
22. A	23. B	24. C	25. C	26. D	27. A	

Chapter 7. Distillation

1. B	2. C	3. A	4. A	5. B	6. D	7. B
8. A	9. C	10. B	11. D	12. D	13. C	14. A
15. C	16. D	17. A	18. B	19. C	20. A	21. C
22. D	23. D	24. C	25. A	26. B	27. C	28. D
29. A	30. A	31. B	32. D	33. C	34. B	35. A
36. C	37. A	38. A	39. A	40. A.		

Chapter 8. Drying

1. A	2. B	3. C	4. B	5. B	6. D	7. B
8. A	9. A	10. A	11. B	12. D	13. C	14. D
15. A	16. B	17. A	18. B	19. C	20. B	21. C
22. D	23. A	24. C	25. D	26. D	27. B	28. B
29. C	30. B	31. B	32. D	33. B	34. A	35. D
36. A	37. C	38. C	39. A	40. A	41. A	42. D
43. C	44. B	45. D	46. B	47. C	48. D	49. D
50. A	51. B	52. A	53. D.			

Chapter 9. Mixing, Section I: Mixing of Solids

1. D	2. C	3. C	4. B	5. A	6. D	7. C
8. A	9. C	10. A	11. A	12. A	13. B	14. A

15. D	16. B	17. C	18. D	19. A	20. C	21. C
22. A	23. D					

Section II: Mixing of Liquids

1. C	2. C	3. A	4. A	5. B		

Section III & IV : Mixing of Immiscible Liquids, Semisolids Mixing

1. A	2. D	3. B	4. A	5. C	6. D	7. C
8. A	9. D	10. A	11. A	12. D	13. A	14. B
15. D	16. A	17. C	18. D			

Chapter 10. Filtration

1. A	2. B	3. D	4. B	5. B	6. B	7. B
8. D	9. C	10. B	11. B	12. A	13. D	14. D
15. A	16. C	17. C	18. C	19. D	20. A	21. D
22. D	23. D	24. C	25. D	26. C	27. B	28. D
29. C	30 A	31. C	32. C			

Chapter 11. Centrifugation

1. B	2. A	3. C	4. A	5. A	6. A	7. B
8. B	9. C	10. B	11. A	12. D	13. D	14. C
15. C	16. C	17. C	18. D	19. C	20. B	21. C
22. D	23. C	24. A	25. C			

Chapter 12. Materials of Construction

1. B	2. C	3. B	4. B	5. A	6. A	7. B
8. A	9. D	10. B	11. B	12. C	13. D	14. D
15. A	16. C	17. A	18. A	19. D	20. A	

Chapter 13. Corrosion

1. C	2. B	3. A	4. C	5. A	6. C	7. C
8. C	9. D	10. C	11. C	12. B	13. D	14. D
15. B						

Chapter 14. Transportation of Solids

1. D	2. A	3. C	4. A	5. D	6. D	7. A
8. B	9. C	10. D	11. D	12. B	13. A	14. D
15. D	16. D	17. D	18. C	19. A	20. A	21. D
22. B	23. D	24. B	25. A			

APPENDIX-III

Definitions and Meanings

Actual screen : A screen which does not give perfect separation about the cut diameter of the powder.

Agitation : Refers to the induced motion of a material in a specified way, usually in a circulatory pattern inside a container.

Attrition : It involves breaking down of the material by rubbing action between two surfaces.

Axial flow of liquids : The flow of liquid that acts in a direction parallel to the impeller shaft.

Azeotropic distillation : It is a distillation method in which azeotropic mixture is broken by the addition of a third substance, which forms a new azeotrope with one of the components.

Azeotropic solution : It is a solution which distilled unchanged at a constant temperature.

Bernoulli's theorem : States that in a steady state, ideal flow of a incompressible fluid, the total energy per unit mass, which consist of pressure energy, kinetic energy and datum energy, at any point of fluid is constant.

Binary liquids : Are those liquids which are miscible with one another in all proportions.

Biological corrosion : The metabolic action of microorganisms can either directly or indirectly causes deterioration of a metal (corrosion).

Black body : It is a body that radiates maximum possible amount of energy at a given temperature.

Blending : It is mixing of powders smoothly and inseparably together.

Bound water : Is the minimum water held by the material that exerts an equilibrium vapour pressure less than the pure water at the same temperature.

Bulk transport : Is the movement of a large portion of a material from one location to another location in a given system.

Calandria : It is a system compartment, which consists of a number of tubes fitted in a vessel and is usually included in an evaporator.

Centrifugal force : It is due to inertia of a rotating body and it acts on the rotating body in a direction away from the point or axis of rotation.

Centrifugation : It is a unit operation employed for separating the constituents present in a dispersion with the aid of centrifugal force.

Clarification : It is a process of separation of liquids containing solids not exceeding 1.0 %.

Classification methods (in sizing) : These are the particle separation methods based on the principle of settling rate of particles into different fractions of narrow particle size range.

Compression : It is a means by which the material is crushed between rollers by the application of pressure.

Conduction : It is a process in which heat flow in a body is achieved by the transfer of momentum of individual atoms or molecules without mixing.

Convection : It is a process in which heat flow is achieved by actual mixing of warmer portions with cooler portions of the same material.

Corrosion : Is a reaction of a metallic material with its environment, which causes a measurable change to the material that can result in a functional failure of the metallic component or a of a complete system.

Critical quality attributes : These are defined as properties or characteristics, namely physical, chemical, biological or microbiological that should be within the appropriate limit (range or distribution), in order to ensure the desired quality.

Critical process parameters (CPP) : These are the process parameters that influences the critical quality attributes (CQA) and that must be controlled with a predefined limits so as to ensure its fitness for use in subsequent steps.

Cutting : It is a means of tearing the material by a sharp blade.

Dalton's law : It states that the total pressure exerted by an ideal gaseous mixture is equal to the sum of the individual partial pressures of the component gases, if alone were present and occupy the total volume.

Depth filtration : It is a filtration process, in which the slurry penetrates to a point where the diameter of solid particles is greater than that of the tortuous void or channel.

Destructive distillation : It is a distillation method in which the distillate is a decomposition product of the constituents of the organic matter burnt in the absence of air.

Distilland : The feed liquid mixture to be distilled.

Distillate (condensate) : The liquid condensed during distillation.

Distillation : It is a separation of the components of a liquid mixture by processes involving vapourization and subsequent condensation at another place.

Downstream stage : The production stage that involves processing the materials collected during a reaction into a finished product.

Drop-wise condensation : It is a process in which the condensed liquid collects as drops that may range from microscopic size up to drops that are seen with the naked eye.

Dry steam : It is the steam in which water is completely absent.

Drying : It is a process of removal of small amounts of water or liquid from a material by the application of heat.

Elutriation : It is a method of separation of particles (in a powder) based on the low density of fine particles and high density of the coarse particles using fluid flow.

Energy balance : The law of conservation of energy states that the energy output must be same as the energy input in any process.

Entrainment : It is a term used to describe the loss of liquid frothing or 'blowing over' during evaporation.

Equilibrium moisture content (EMC) : Is the amount of water present in the solid, which exerts a vapour pressure equal to the vapour pressure of the atmosphere surrounding it.

Erosion : It is the destruction of a metal by abrasion and attrition caused by the flow of liquids or gases.

Eutectic point : The temperature and pressure at which the frozen solid vapouizes without converting into a liquid.

Evaporation : It is a process of vapourizing large quantities of volatile liquid to get a concentrated product.

Exhaust steam : It is the steam that has a saturation temperature ranging from 215 to 230 °F.

Extractive distillation : It is a distillation method in which azeotropic mixture is broken by the addition of a third substance, which is relatively nonvolatile compared to the components to be separated.

Film type condensation : A process in which the condensed liquid wets the surface on which it is condensing and forms a continuous film.

Filter aid : It forms a surface deposit which screens out the solids and also prevents plugging of the supporting filter medium.

Filtration centrifuge : A centrifuge in which solids are retained by porous medium allowing liquid to rush out due to centrifugal effect.

Filtration : Is a process of separation of solids from a fluid by passing the same through a porous medium that retains the solids, but allows the fluid to pass through.

Flash distillation (equilibrium distillation) : It is a distillation method in which the entire liquid mixture is suddenly vapourized (flash) by passing the feed from a high pressure zone to a low pressure zone.

Flaw in a particle : It is a structural weakness that may develop into a crack under strain.

Fluid flow : It is the flow of substances that do not permanently resist distortion.

Fluid statics : It deals with the fluid at rest in equilibrium.

Forced convection : It is a heat transfer process, in which mixing of fluid is achieved by a stirrer or agitator or pump the fluid for recirculation.

Fourier's law : This law states that the rate of heat flow through a uniform metal is proportional to the area, the temperature drop and inversely proportional to the length of the path of flow.

Fractional distillation : It is a distillation method in which vapourization of liquid mixture gives rise a to a mixture of constituents from which the desired one is separated in a pure form.

Fractionating column : It is a special type of still-head in which condensation and revapourization take place simultaneously.

Free moisture content (FMC) : Is the amount of water that is free (easy) to evaporate from the surface.

Free settling of particles : It implies that particles settle independently, without any interference of other particles in the fluid.

Galvanic corrosion : Corrosion associated with the flow of current to a less-active metal (cathode) from a more-active metal (anode) in the same environment.

Grey body : It is a body whose absorptivity is constant at all wavelengths of the radiation, at a given temperature.

Heat exchanger : It is a heating device used for transferring heat from one fluid (hot gas or steam) to another fluid through a metal wall.

Heat interchanger : It is a heating device used for transferring heat from one liquid to another liquid or from one gas to another gas through a metal wall.

Hindered settling of particles : It implies that the light particles are pushed by heavier particles while settling in a fluid.

Ideal screen : A screen which sharply separates the feed mixture in such a way that the smallest particle in the oversize will be just larger than the largest particle in the undersize.

Ideal solution (Perfect solution) : It is a solution in which the attractions between unlike-molecules are of the same order as between like-molecules.

Impact : It involves the operation of splitting the material apart, when a lump of material strikes against the rotating hammers.

Key process parameters (KPP) : These are defined as properties that influence product quality or process effectiveness.

Laminar flow (viscous flow) : It is a flow in which the fluid particles move in layers or laminar with one layer sliding over the other.

Laminar mixing : Is the mixing of two dissimilar liquids through laminar flow, i.e. the applied shear stretches the interface between them.

Latent heat of steam : It is the heat required to convert one kg of liquid water at its boiling point (100 °C) or saturation temperature to one kg of water vapour without changing the temperature.

Latent heat of vapourization : Is defined as the quantity of heat required to convert a unit mass of the liquid at its boiling point from the liquid to the vapour state without a change in temperature.

Manometers : These are the devices used for measuring the pressure difference at a point of fluid.

Material balance : The law of conservation of matter states that material cannot be destroyed or created, it can be changed from one form to another.

Mechanical pressure gauges : These are the mechanical elements used for measuring the pressure.

Miscible liquids : These liquids are miscible in all proportions.

Mixing : Is a process that tends to result in a randomization of dissimilar particles within a system.

Mixing : Putting together in one mass or assemblage with more or less thorough diffusion of the constituent elements among one another.

Molecular diffusion : Is the mixing at molecular level in which molecules diffuse due to thermal motion.

Molecular distillation (Short path distillation or evaporative distillation) : It is a distillation method in which each molecule in the vapour phase travels mean free path and gets condensed individually without intermolecular collisions, on application of vacuum.

Natural convection : It is the heat transfer process in which mixing of fluid is accomplished by the natural currents (set up), when body of fluid is heated.

Over-size powder : The material that remains on the given screening surface.

Partially miscible liquids : These are liquids which are miscible in one another at one particular proportion.

Pitch : It is the distance the propeller would move through the fluid per rotation, if slippage does not occur.

Pressure head : It is defined as the height of a column of liquid of known density which is numerically equal to the pressure.

Process parameters : These are the input variables to the process that may affect the outcome.

Process steam : It is the steam that gives a temperature of 200 °F.

Quality : The totality of features and characteristics of products or services that bear on its ability to satisfy stated or implied needs.

Quality : It is the suitability of either a drug substance or a drug product for its intended use.

Quality attributes (QAs) : These are referred as physical, chemical, biological and microbiological properties or characteristics of a product.

Radial flow of liquid : It is the flow of liquid that acts in a direction vertical to the impeller shaft.

Radiation : It is a process in which heat flows through space by means of electromagnetic waves.

Raoult's law : It states that the partial vapour pressure of each volatile constituent is equal to the vapour pressure of the pure constituents multiplied by its mole fraction in the solution at a given temperature.

Real solution (Perfect solution) : The solution which does not obey ideal solution behavior or which does not obey Raoult's law.

Reynolds number : It is a ratio of inertial force to viscous force of a flowing liquid.

Saturated steam : It is the steam at a temperature of boiling point of water (100 °C) at that pressure.

Sedimentation centrifuge : A centrifuge that produces sedimentation of solids based on the difference in the densities of two or more phases of the mixture.

Sensible heat (or liquid heat) : It is the heat that is utilized to increase the temperature of one kg of water from the freezing point (0 °C) to the temperature of formation of steam (100 °C), i.e. saturation temperature.

Sensible heat : In humidification, it is the heat achieved without addition and subtraction of moisture content.

Settling : It is a process of sedimenting the particles of different sizes.

Sieve number : It indicates the number of meshes per linear length of 0.0254 m (one inch).

Simple distillation : Is a process of converting a single constituent from a liquid (or mixture) into its vapour, transferring the vapour to another place and recovering the liquid by condensing the vapour, usually by allowing it to come in contact with the cold surface.

Size reduction : Is a process of reducing large solid unit masses (vegetable or chemical substance) into small unit masses, coarse particles or fine particles.

Size separation : It is a unit operation that involves the separation of a mixture of various sizes of particles into two or more portions by means of screening surfaces.

Steady state system : The system is said to be in steady state, if the operating conditions do not vary with them.

Steam distillation : It is a method of distillation carried with the aid of steam and is used for separating of high boiling substances from nonvolatile impurities.

Stoichiometry : It means carrying out the calculations based on quantitative relationships.

Sublimation : It is a process in which direct change of solid into vapour takes place without converting into a liquid phase.

Superheated steam : It is the steam having temperature higher than 100 °C and in which all water is completely vapourized and further contains sensible heat.

Supersaturated solution : Is one that contains more of the dissolved solute than it would normally contain in a saturated solution at a define temperature.

Surface coefficient : It is the conductive capacity of the stagnant film for the transfer of heat.

Surface filtration : It is a screening action (filtration process) by which pores or holes of the medium prevents the passage of solids.

Tangential flow of liquid : It is the flow of liquid that acts in a direction tangent to the circle of rotation around the impeller shaft.

Thermal conductivity : It is the reciprocal of thermal resistance.

Tie substance : It is a material that comes into the process in just one stream and leaves unchanged in another stream.

Transducer : It is a device that takes one form of energy from a measuring source (air compressed from a cylinder) and supply energy of a different kind (mechanical power).

Turbulent flow : A flow is said to be turbulent, if the Reynolds number is more than 4000 in a pipe.

Turbulent flow : It is the flow in which the fluid particles continuously transfer momentum to adjacent layers.

Turbulent mixing : Is mixing due to turbulent flow, which results in random fluctuation of the fluid velocity at any given point within the system.

Unbound water : Is the water (moisture) held by the material that exerts an equilibrium vapour pressure equal to that of pure water at the same temperature.

Under-size powder : The material that can pass through the screening surface.

Unit operation : A process frequently consists of a fewer number of distinct individual steps. Each step is called unit operation.

Unit process : It is one in which several unit operations are combined in a sequence to achieve the objectives of a chemical or physical process.

Upstream stage : A production stage that involves searching for and using new materials in the process.

Vacuum : It is space in which the pressure of gas is low compared to what is normal, i.e. atmospheric pressure.

Variable area meter : It is a device that measures the area of flow, so as to produce a constant head differential.

Variable head meter : It is a device that measures the variation in the pressure across a fixed constriction placed in the path of flow consisting of a constant area.

Viscous flow : A flow is said to be viscous if the Reynolds number is less than 2000 in a pipe or the fluid flow in layers.

Volatility : Is the equilibrium partial pressure of the substance in the vapour state divided by the mole fraction of the substance in the solution.

Vortex : It is a strong circulatory flow pattern manifests near the impeller shaft.

Wet steam : It is the steam in which liquid water is also present in a definite proportion.

Young's modulus : The ratio of the longitudinal stress to the longitudinal strain within elastic limits.

Zeotropic mixture : It is a mixture whose total vapour pressure is always intermediate between those of pure components.

APPENDIX-IV

All in Twos – Know Them Well

Anodic metals for copper : zinc, iron.

Azeotropic mixtures with maximum boiling point : water-ethanol, benzene-ethanol.

Azeotropic mixtures with minimum boiling point : chloroform-acetone, pyridine-acetic acid

Batch type solids mixers : double cone blender, sigma blade blender.

Binary liquids : ethyl alcohol-water, benzene-carbon tetrachloride.

Clarifying filters : metafilter, chamber filter.

Cohesive solid mixers : planetary mixer, sigma blender.

Cohesive solids : wet clay, wet calcium carbonate.

Concentration terms : moles, molality.

Continuous type of solid mixers : Barrel mixer, zigzag blender.

Convective mixing equipment : ribbon mixer, planetary mixer.

Conveyors work under closed conditions : screw conveyor, pneumatic conveyor.

Conveyors work under open conditions : belt conveyor, flight conveyor.

Critical process parameters : moisture content, flow properties.

Critical quality attributes : efficacy, safety.

Diffusive mixing equipment : V cone blender, double cone blender.

Dimensionless numbers : Reynolds number, Sherwood number.

Downstream process : extraction, crystallization.

Dryers for heat sensitive products : freeze dryer, spray dryer.

Elastic materials : clarithromycin, microcrystalline cellulose.

Equipment materials, sterilizable : stainless steel, aluminum.

Evaporators with cyclone separator : falling film evaporator, forced circulation evaporator.

Evaporators with long tubes : climbing film evaporator, falling film evaporator.

Evaporators with short tubes : standard vertical tube evaporator, basket type evaporator.

Fibrous materials : glycyrrhiza, ginger.

Filter aids : keiselguhr, paper pulp.

Filter media : cloth woven material, prefabricated porous solid unit.

Filters in fermentation : drum filter, frame and plate filter.

Filtration centrifuges : perforated basket centrifuge, semicontinuous centrifuge.

Flammable materials : dextrin, sulphur.

Fluid flow rate meters : venturi meter, rotameter.

Fractionating columns for distillation : Widmer column, bubble cap column.

Free flowing solids mixers : double cone blender, V cone blender.

Friable materials : sucrose, salt.

Glass containers for parenteral uses : borosilicate glass, treated sodalime glass.

Hard materials : iodine, pumice.

Heat exchangers : shell-and-tube heater, multipass heater.

Heat interchanges : double pipe heat interchanger, liquid-liquid heat interchanger.

Heating media : steam, solar heater.

Hygroscopic materials : potassium carbonate, sodium hydroxide.

Idlers of belt conveyor : snubber idlers, troughing idlers.

Immiscible liquids mixers : Silverson emulsifier, colloid mill.

Impellers for liquid mixing : propellers, turbines.

Industrial sieving equipment : Rotex screens, bag filter.

Laboratory centrifuges : ultracentrifuge, angle centrifuge.

Liquid flow patterns : radial, axial.

Manometers : mercury manometer, alcohol manometer.

Materials of filters for aseptic screening : Nylon, polyvinylchloride fibre.

Mechanical method of size reduction : cutting, attrition.

Mechanical pressure gauges : Bourdon pressure gauze, Bellows pressure gauge.

Mechanisms of drying : diffusion theory, capillarity theory.

Mechanisms of filtration : straining, entanglement.

Mechanisms of liquid mixing : bulk transport, turbulent mixing.

Mechanisms of size reduction : impact, compression.

Mechanisms of solid-solid mixing : convective mixing, shear mixing.

Metals of high thermal conductivities : copper, silver.

Metals of low thermal conductivities (insulators) : brick, water.

Miscible liquids mixers : airjet mixer, jet mixer.

Molecular distillation equipment : falling film molecular still, centrifugal molecular still.

Moving bed dryers : drum dryer, tunnel dryer.

Non-cohesive solids : dry sand, plastic chips.

Nonferrous materials, aluminum, lead.

Nonmetal materials : glass, rubber.

Non-porous solids : talc, zinc oxide.

Official products prepared by simple distillation : spirit of nitrous ether, aromatic spirit of ammonia.

Pneumatic dryer : spray dryer, fluid bed dryer.

Precipitation method of size reduction : insulin, calcium carbonate.

Pressure filters : plate and frame filter, metafilter.

Process parameters : heating/cooling rate, batch size

Quality attributes : assay, dissolution.

Radiation dryer : IR dryer, microwave dryer.

Sample collection techniques : thief probing, scoop sampling.

Sedimentation centrifuges : supercentrifuge, conical disc-centrifuge.

Semisolid mixers : triple roller mill, sigma mixer.

Shapes of holes of screens : round holes, square holes.

Shear mixing equipment : rotor mixer, silverson emulsifier

Sieves : woven wire sieves, bolting cloth sieves.

Size reduction methods : mechanical, precipitation.

Size reduction mills by attrition : fluid energy mill, ball mill.

Size reduction mills by compression : roller mill edge runner mill.

Size reduction mills by cutting : cutter mill, drum straw cutter

Size reduction mills by impact : hammer mill, fluid energy mill.

Size reduction mills by shear : colloid mill, edge runner mill

Solids conveyors : belt conveyor, bucket conveyor.

Static bed dryers : tray dryer, freeze dryer.

Static type mixers : sigma blender, ribbon blender.

Steam traps : float type, bucket type.

Sterile product filters : cartridge filter, chamber filter.

Sterilizable size reduction mills : fluid energy mill, ball mill.

Storage containers : bins, silos.

Substances prepared by vacuum distillation : malt extract, anthraquinones.

Substances purified by molecular distillation : dibutylphthalate, vitamin E.

Substances purified by steam distillation : camphor, almond oil.

Synthetic rubbers : Neoprene, butyl rubber.

Theories of filtration : Poiseuille theory, Darcy's theory.

Thermolabile drugs : aspirin, ascorbic acid.

Thermoplastics : polythene, polyvinyl chloride (PVC).

Thermosetting plastics : bakelite, melamine.

Tie substances : dissolved solids, ash.

Types of filtration : surface filtration, depth filtration.

Unit operations : drying, mixing.

Unit processes : manufacture of common slat, production of paraacetamol.

Upstream processes : active pharmaceutical ingredient, living cells.

Variable area meters for measuring flow of fluids : rotameter.

Variable head meters for measuring flow of fluids : orifice meter, venture meter.

Weaving methods of sieves : plain weaving, twilled weaving.

APPENDIX-V

Bibliography

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APPENDIX-VI

Fractions and Multiplications of Units

(A) Greek Alphabets

A	α	Alpha	N	ν	Nu
B	β	Beta	Ξ	ξ	Xi
Γ	γ	Gamma	O	o	Omicron
Δ	δ	Delta	Π	π	Pi
E	ε	Epsilon	R	ρ	Rho
Z	ζ	Zeta	Σ	σ	Sigma
Θ	θ	Theta	U	υ	Upsilon
I	ι	Iota	Φ	ϕ	Phi
K	κ	Kappa	C	χ	Chi
Λ	λ	Lambda	Ψ	ψ	Psi
M	μ	Mu	Ω	ω	Omega

(B) SI Units

Fraction	*Prefix*	*Abbreviation*	*Power*	*Prefix*	*Abbreviation*
10^{-1}	deci	d	10^{1}	deca	da
10^{-2}	centi	c	10^{2}	hecta	h
10^{-3}	milli	m	10^{3}	kilo	k
10^{-6}	micro	μ	10^{6}	mega	M
10^{-9}	nano	n	10^{9}	giga	G
10^{-12}	pico	p	10^{12}	terra	T
10^{-15}	femto	f			
10^{-18}	atto	a			

APPENDIX-VII

(A) Some Notations of Units and their Abbreviations in SI Units

Property	*Units in full names*	*Abbreviations for the units*
Acceleration due to gravity	metre per second square	m/s^2
Amount of heat	joule	J
Capacity of a pump	metre cube per hour	m^3/h
Centrifugal force	newton	N
Concentration	Moles Molarity Normality Molality	Mol M N m
Density	kilogram per metre cube	kg/m^3
Displacement in pump	metre cube per minute	m^3/min
Drop in head	metre	m
Energy	joule	J
Enthalpy per unit mass	joules per kilogram	J/kg
Film coefficient or Surface coefficient	watt per metre square·Kelvin	$W/m^2 \cdot K$
Force	newton	N
Frequency	hertz	Hz
Gravitational force	newton	N
Heat transfer	joule	J
Heat transfer coefficient	watt per metre square·Kelvin	$W/m^2 \cdot K$
Heat transfer rate	joule per second	J/s
Height or length	metre	m
Length	metre	m
Mass	kilogram	kg
Power	watt	W
Pressure	pascal	Pa
Pressure drop	pascal	Pa
Pressure head	metre	m

Property	*Units in full names*	*Abbreviations for the units*
Rate of discharge of liquid	meter cube per minute	m^3/min
Rate of drying	kilogram per hour	kg/h
Rate of entry of feed	kilogram per hour	kg/h
Specific energy	millijoule per kilogram	mJ/kg
Specific surface	metre square per meter cube	m^2/m^3
Speed of rotation	Revolutions per second	r/s
Steam pressure	pascal	Pa
Stefan Boltzmann constant	watt per metre square $Kelvin^4$	$W/m^2 \cdot K4$
Surface area	metre square	m^2
Surface energy	millijoules per metre square	mJ/m^2
Temperature	Degree Kelvin Degree Celsius	K °C
Tensile strength	megapascal	Mpa
Thermal conductivity	watt per metre square·Kelvin	$W/m^2 \cdot K$
Time	second (or minute or hour)	s (or min or h)
Velocity	metre per second	m/s
Viscosity	pascal.second	Pa·s
Volume	metre cube (or litre)	m^3 (or l)
Work done	watt hour	W·h
Young's modulus	megapascal	Mpa

(B) Some Important conversions in SI Units

Pascal (Pa)	$= N/m^2$	$= kg/m \cdot s^2$
Newton (N)	= kg/m	
Joule (J)	$= N \cdot m$	$= kg.m^2/s^2$
N·m	= J	
N·m/s	= J/s	= W
J/s	= W	
W	$= N \cdot m/s$	

APPENDIX-VIII

Inter-Conversion of Units

TABLE-1

FPS to SI Units

Measurement	*Unit*	*Conversion factor*	*Reciprocal*
Area	1 ft^2 1 in^2	9.290×10^{-2} m^2 6.452×10^{-4} m^3	10.764 1550
Density	1 lb/ft^3 1 lb/in^3	16.0185 kg/m^3 27.680 kg/m^3	6.243×10^{-2} 3.613×10^{-5}
Energy, work and power	1 Btu	1.055×10^3 joules	9.4781×10^{-4}
Force	1 lbf	4.448 N	0.225
Heat transfer coefficient	Btu/s·ft^2 °F	20.44 kW/m^2·K	4.89×10^{-2}
Length	1 foot 1 inch	0.3048 meter 2.54×10^{-2} meter	3.2808 39.370
Mass	1 pound (lb) 1 US ton	0.4536 kg 9.072×10^{-4} kg	2.2046 11.02×10^2
Mass flow rate	1 lb/s	0.454 kg/s	2.205
Power	1 ft.lbf/s 1 lbf·ft	1.356 W 1.355×10^{-3} kJ	0.738 7.38×10^2
Pressure	1 lbf/in^2 1 atm. 1 bar 1 inHg	6895 Pa 1.013×10^2 kPa 100 kPa 3386 Pa	1.45×10^{-4} 9.87×10^{-3} 0.01 2.95×10^{-4}
Stress	1 lbf/in^2	6.8948×10^3 kPa	1.4504×10^{-4}
Thermal conductivity	1 Btu·ft/h·ft^2·°F 1 Btu·in/h·ft^2·°F	1.730 W/m·K 0.1442 W/m·K	0.578 6.935
Thermal resistance	1°F·ft^2·h/Btu 1 lbf/ft^2	1.761×10^2 K·m^2/kW 4.788×10^{-2} kPa	5.679×10^{-3} 20.886
Vacuum	1 inHg (60°F) 1 inH^2O (39.2°F)	3.377 kPa 0.2491 kPa	0.2961 4.0145
Velocity	1 ft/s 1 in/s	0.305 m/s 0.0254 m/s	3.281 39.37

Measurement	*Unit*	*Conversion factor*	*Reciprocal*
Viscosity	1 lbf·s/in^2 1 lbf·s/ft^2	6.894×10^3 Pa·s 47.88 Pa·s	1.451×10^{-4} 2.0886×10^{-2}
Volume	1 ft^3 1 in^3 1 US gallon	2.832×10^{-2} m^3 1.693×10^{-5} m^3 4.54×10^{-3} m^3	35.315 61.024 220.264

TABLE-2

Interconversion of Units (Fundamental and Derived) with Conversion Factors

Unit	*Conversion factor × unit*	*Reciprocal*
1 foot	= 30.48 cm (or ml)	0.03281
1 pound (lb)	= 453.6 gram	2.2046×10^{-3}
1 cm^2	= 1.639×10^{-5} m^2	6.1024×10^4
1 dyne	= 0.01 mN	100
1 dyne/cm^2	= 0.1 Pa	10
1 cm H_2O (4°C)	= 9.80×10^{-2} kPa	10.205
1 cal	= 4.184×10^{-3} kJ	239.00
1 erg	= 1.0×10^{-7} J	10^7
1°C·m^2·h/kcal	= 8.604×10^2 K·m^2/kW	1.162×10^{-3}
1 cal·m/s·cm^2·°C	= 4.184×10^2 W/m·K	2.39×10^{-3}
1 mmHg	= 6.895 kPa	0.145
1 cal/s·cm^2·°C	= 41.84 kW/m^2·K	2.39×10^{-2}

TEMPERATURES

TABLE-3

Interconversion of Temperature and Relevant Equations

R (Rankine)	= (1/18) K (Kelvin)
1 K (Kelvin)	= 1.8 R (Rankine)
T R (Rankine)	= T°F + 459.67
T°F (Fahrenheit)	= T R – 459.67
T°C (Celcius)	= (°F – 32)/1.8°C
T°F (Fahrenheit)	= 32 +1.8°C
ΔT°C	= 1.8 ΔT°F = ΔT K

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