Module 3
Mass Transfer

MASS TRANSFER – DIFFUSION, ABSORPTION, LEACHING, EXTRACTION, ADSORPTION AND DRYING.

3.1.1 State law of Conservation of mass

3.1.2 Define diffusion and Fick's law of diffusion

3.1.3 Explain the mechanism of absorption, Condition of equilibrium between gas and liquid, Henry's law

3.1.4 Explain the factors controlling the rate of absorption

3.1.5 Explain the concept of NTU and HTU, derivation and simple problems

3.1.6 Explain the various packing materials and their characteristics

3.1.7 Explain the working of Packed Tower, flooding and channeling in packed columns

3.1.8 Define leaching and its applications– batch and continuous leaching , heap leaching

3.1.9 Explain the operation of Boll man extractor, horizontal and vertical type

3.1.10 Define liquid- liquid extraction, the terms raffinate and extract

3.1.11 Mention the various extraction equipments

3.1.12 Explain the construction details and working of Mixer settler

3.1.13 Explain adsorption, physical and chemical adsorption and the various types of adsorbents

3.1.14 Mention the purpose and applications of drying

3.1.15 List the various drying equipments

3.1.16 Explain the working of Tray drier and Spray drier

Mass Transfer

- Transfer of material from one homogeneous phase to another with or without phase change
- Takes place between two phases across an interface
- Complex phenomenon which occurs in all unit operations

  Extraction – transfer of solute

  Evaporation
  Drying
  Distillation

  Simultaneous heat and mass transfer

- Occurs through different mechanisms such as molecular diffusion, convection& turbulent mixing

Law of Conservation of Mass

- Established in 1789 by French Chemist Antoine Lavoisier

- The law of conservation of mass states that mass in an isolated system is neither created nor destroyed by chemical reactions or physical transformations.

- Simply , the mass of a substance produced (products) by a chemical reaction is always equal to the mass of the reacting substances.

$$2\,Mg\,(s) + O_2\,(g) = 2\,MgO\,(s)$$

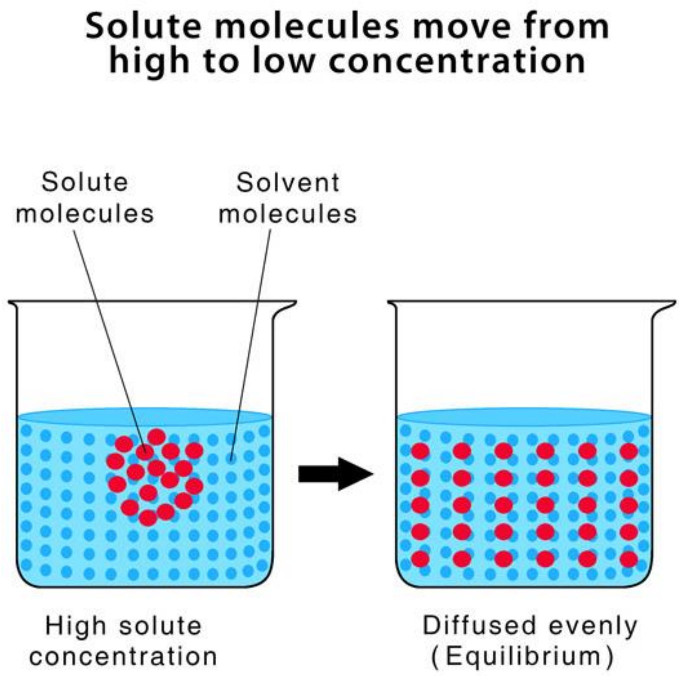
48.6 g 32 g 80.6 g

Diffusion

- It is the movement of an individual component through a mixture from a region of higher concentration to a region of lower concentration at fixed temperature and pressure with or without the help of an external force, until the concentration equalizes throughout the medium

Diffusion is important for the following reasons:

- ✓ During the process of respiration, this process helps in diffusing the carbon dioxide gas out through the cell membrane into the blood.
- ✓ Diffusion also occurs in plant cells. In all green plants, water present in the soil diffuses into plants through their root hair cells.



Types of diffusion

- Molecular diffusion – results from the random movement of the individual molecules in a gas, liquid or a solid as a thermal motion.
- Eddy or turbulent diffusion – movement of molecules occurs with the help of an external force (mechanical stirring and convective movement of fluid)

Molecular diffusion	Eddy diffusion
Slow process	Fast process
Occurs in stationary fluids (fluids at rest and fluids in laminar flow)	Occurs in fluids in turbulent
Molecular transfer – transfer of material in presence of concentration gradient (in stationary fluids/ in laminar flow fluids)	Eddy transfer – transfer of material in presence of concentration gradient (in fluids under turbulent conditions)

- Mass concentration – mass concentration of a species A in a solution is the mass of species A per unit volume of the solution, equivalent to the density of A, denoted by ρ_A

- Molar concentration – number of moles of species A in a solution is the number of moles of species A per unit volume of the solution

$$C_A = \rho_A / M_A \;;\; M_A \text{ – molecular weight of component A}$$

- Mass fraction - mass fraction x_A of a species A in a a solution is defined as the ratio of mass concentration of species A to the mass density of the solution(ρ)

$$x'_A = \rho_A / \rho$$

- Mole fraction- mole fraction (x_A) of a species A in a solution is defined as the ration of molar concentration of A to the molar concentration of the solution

$$\mathbf{x_A = C_A \ / \ C}$$

- Flux- mass transfer flux of a given species (vector quantity) is defined as the amount of that species (in either mass/molar units) that is transported per unit time across a unit area

- Mass flux (i) - rate of mass flow per unit area (mass of species that passes through a unit area per unit time)

- Molar flux – defined as the moles of species that passes through a unit area per unit time

Fick’s Law of Diffusion

- Derived by Adolf Fick in 1855
- Mathematical statements describing how particles under random thermal motion tend to spread from a region of higher concentration to a region of lower concentration to equalize concentration on both the regions.
- Fick's first law of diffusion states that the flux is directly proportional to the concentration gradient.

$$J \propto \frac{dc}{dx} \quad \text{OR} \quad J = -D\frac{dc}{dx}.$$

Where, J = molar flux ((kmol/m^2.s)

dc = change in concentration of material (kmol/m^3)

dx = change in the distance , m

D = proportionality constant, known as molecular diffusivity or diffusion coefficient (m^2.s)

- The negative sign indicates that diffusion occurs in the direction of decrease in concentration whereas flux is a positive quantity because it increases continuously during the process.

Absorption/ Gas Absorption

- Unit operation used in chemical industry to separate gases by washing or scrubbing a gas mixture with a suitable liquid

- The fundamental principle underlying the process of gas absorption are the solubility of the absorbed gas and the rate of mass transfer. One or more constituents of the gas mixture dissolves or is absorbed in the liquid and can be thus removed from the mixture. In some systems ,this gaseous constituents forms a physical solution with the liquid or the solvent, and in other cases, it reacts with the liquid chemically.

- The absorber may be a packed column, plate column, spray column, bubble column, wet scrubbers, stirred tanks.

- In gas absorption, the soluble component of a gas mixture is called solute gas, the insoluble component is called inert gas or carrier gas and the liquid used for absorption purpose is called the absorbent or solvent

$$\text{Solute} + \text{Carrier gas} \xrightarrow{\text{Absorbent}} \text{Solute absorbed in absorbent} + \text{Carrier gas}$$

- Gas absorption is exothermic in nature, so this operation demands a cooling provision and is normally carried out at low temperatures since the solubility of a solute gas in a given solvent is high at lower temperatures.

- Example : washing of ammonia from a mixture of ammonia and air using water as solvent

Here, since ammonia is soluble in water, air is almost insoluble and water doesn't vaporize to an appreciable extent in the gas mixture at the ambient temperature, the only transfer is of ammonia from the gas phase to the liquid phase.

Henry’s law

- Henry's Law is concerned with the solubility of a gas in a liquid to form an ideal dilute solution
- At a constant temperature, the amount of a dissolved gas in a liquid is directly proportional to the partial pressure of that gas in equilibrium with that liquid.
- For dilute solutions of most gases, the equilibrium relationship is given by Henry’s law

$$P_A = H.\, x_A\,,$$

where P_A is the partial pressure of the solute gas A in the gas phase

x_A is the Mole fraction of the solute gas A in the liquid phase

H is the Henry’s law of constant.

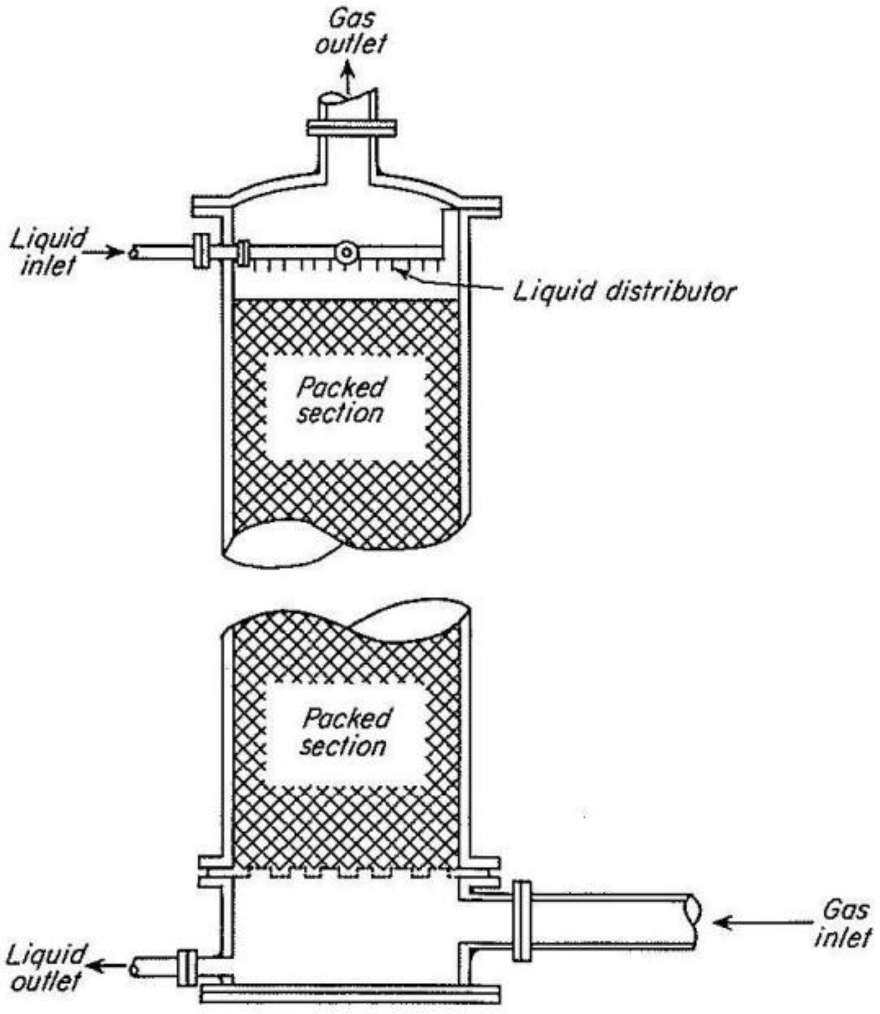
Partial pressure - pressure exerted by an individual gas (from particles of that particular gas) in a mixture is known as its **partial pressure**.

Gas Absorption Equipment's

- Mechanically agitated vessels
- **Packed Columns/towers – commonly practised at industrial level**
- Plate columns

Packed Columns/ Towers

- Frequently used for gas absorption wherein the liquid is dispersed in the form of film and the gas flows as a continuous phase
- Consists of a vertical cylindrical shell constructed out of metal, plastic, ceramic etc. and filled with suitable packing’s/inert material which offers a large interfacial area for gas-liquid contact for mass transfer between the phases.
- A bed of packing rests on a support plate which offers very low resistance to gas flow.
- Provided with a gas inlet distributing space at the bottom, a liquid inlet and a liquid distributor at the top and gas and liquid outlets at the top and bottom.
- Liquid solvent is introduced from the top through the liquid distributor which wets the surface of packing uniformly.
- Liquid drops down the bed and finally the liquid enriched in the solute to be absorbed called a strong liquor (solute + solvent) leaves the bottom of the column.
- A solute containing gas (rich gas) is introduced from the bottom of the tower and rise upwards through the open spaces in the packing counter current to the flow of the liquid.
- The dilute gas leaves the column from the top of the tower.



Packed Columns/ Towers

Advantages

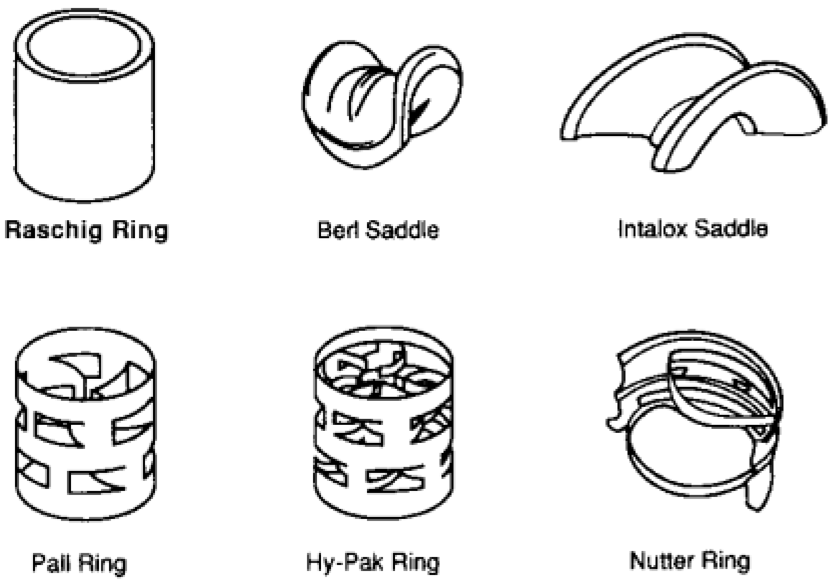
- Minimum structure
- Low pressure drop
- Low liquid hold up
- Handle corrosive liquids and liquids that tend to foam
- Low initial investment

Disadvantages

- Difficult to handle dirty fluids that tends to deposit a sediment on packing's
- Cannot be used when large temperature changes are occurred
- Relatively inflexible
- Distribution of liquid is difficult

Tower Packing's

- Packing section plays an important role providing surface area for the gas and liquid phases to contact upon.
- Small pieces dumped as randomly(not arranged in a particular pattern) or larger structures carefully stacked inside the tower. (Random packing's & Stacked packing's)
- Random packing is cheaper and more common; structured packing is more expensive and more efficient
- Made of ceramics, metals and plastics and vary in size from 6 to 75mm.
- Ceramics provides superior wettability, corrosion resistance at elevated temperature but suffers from poor strength.
- Metals provides superior strength and wettability.
- Plastics, on the other hand, is inexpensive, good strength but have poor wettability at low liquid rate.



Characteristics of Packing materials

- Provide large interfacial area for phase contacting
- Possess good wetting characteristics
- High corrosion resistance
- Relatively cheap/ inexpensive
- Possess enough structural strength
- Chemically inert to the fluids handled in the tower
- Low bulk density so that the weight of the entire packed bed is low which thereby reduces serious support problems
- Provide a larger void volume or empty space in the packed bed so that reasonable throughputs of the phases are handled without excessive pressure drop.

Flooding in Packed columns

- Flooding is a condition where the liquid is "held" in the pockets, or void spaces, between the packing and does not drain down through the packing.
- **Flooding** is excessive accumulation of liquid inside the column.
- Flooding arise when gas or liquid flow is increased beyond the capacity of a column.
- An accumulation of liquid at the top of the packing is an indication of flooding.
- At constant gas flow, an increase in liquid to the column will result to increase in pressure drop until the liquid flooding is attained. At this point, any excess liquid that cannot proceed through will remain at the top of the packing, causing the entire column to be filled with liquid and further intensifying the pressure drop.
- Moreover, at constant liquid flow downwards, increase in gas flow will lead to rise in pressure drop until flooding rate is attained and any further increase will not permit the flow of liquid and consequently, leading to accumulation of liquid at the top of the column and continuous increase in the pressure drop
- Flooding is undesirable because it causes large pressure drop across the packed column resulting in inefficient operation and potential damage to equipment.

Channeling in Packed columns

- This phenomenon takes place when the fluid moving down the column moves towards the region of greatest void space; this occurs at the region near the wall where the packing is not tightly packed.
- Liquid redistributors are used to redirect the fluid flow towards the column centre.

Drying

- Refers to an operation in which moisture of a substance is removed with the help of thermal energy
- Both heat and mass transfer occurs simultaneously
- Heat is transferred from the bulk of the gas phase (drying medium) to the solid phase and mass is transferred from the solid phase to the gas phase in the form of liquid and vapour

Need for Drying

- For reducing the transport cost
- For purifying a crystalline product so that the solvent adhering to the crystals is removed
- To meet the market specifications of solid products set by the customer
- For making a material more suitable for handling and storage
- Preventing corrosion arising due to presence of moisture.

Drying Equipment's

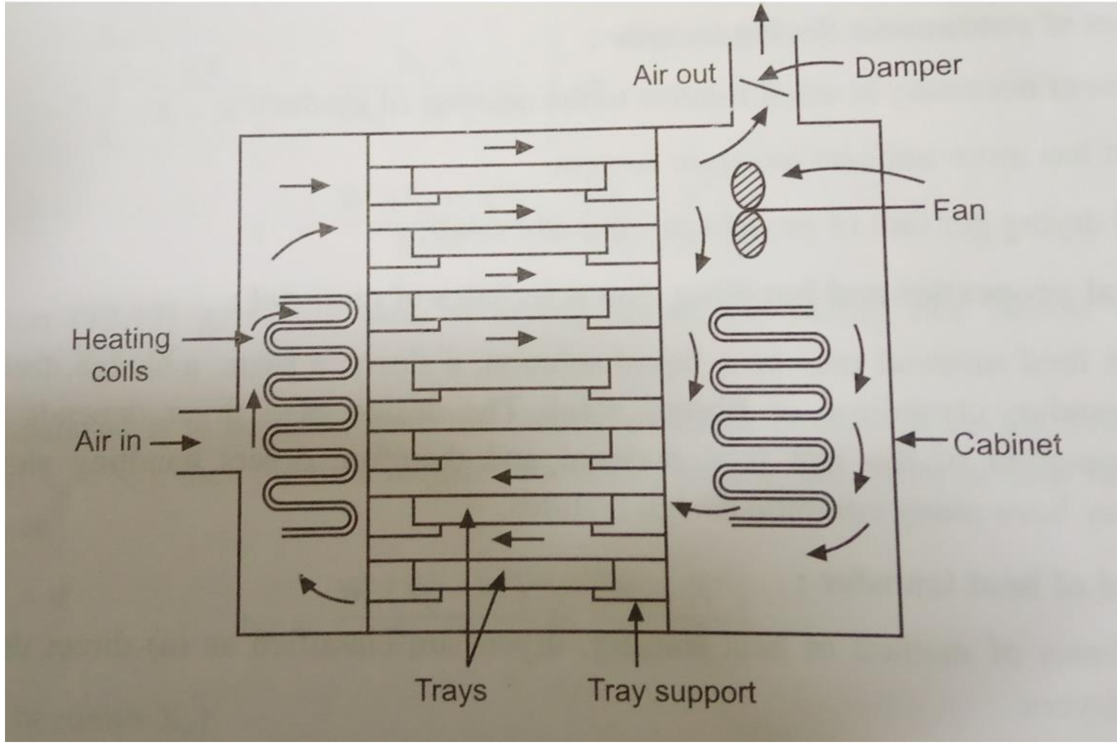
Mode of operation	• Batch Dryers • Continuous Dryers
Physical properties & handling characteristics of the material	• Liquid solution, slurry, paste, free flowing powder, fibrous solid etc. • Design depends on the physical properties of the wet feed material
Method of heat transfer	• Direct dryers • Indirect dryers

Tray/ Cabinet/ Compartment Drier

- Enclosed insulated cabinet / large compartment into which material to be dried is placed on a number of trays
- Trays may be fabricated from sheets, stacked on racks or loaded on trucks
- Provided with inlet and outlet connections for air, heating coil either electrical or steam heating is incorporated in it.
- Steam gas or electrically heated air is used as the drying medium , air circulated in the dryer over the trays by means of a fan fitted at the top
- Trays are generally 600mm wide, 900 to 1500 mm long, 30 to 40 mm deep, made of mild steel, stainless steel etc. and fabricated from sheets of 3 to 6mm thick

Working of Tray Drier

- Material to be dried is spread over the trays and pit into the cabinet and then closed
- Steam continuously passed through the coil, fan started
- Air is heated by heating coil, its relative humidity (capacity to evaporate moisture is increased) and hot air then passes over the trays
- Moisture evaporated from the wet feed, gets added in the air
- Air leaves the drier through the outlet
- Process continued until the solids are dried



ADVANTAGES

- relatively cheap and easy to construct
- Low space requirement
- Ease in cleaning
- No loss of product during drying
- Requires low maintenance

DISADVANTAGES

- Expensive to operate due to high labour requirements for loading and unloading
- Long drying cycles (4 to 48 h per batch)
- Small quantities are handled

Applications - for drying dyes and pharmaceuticals, wet lumpy solids, wet filter cakes

Spray Drier

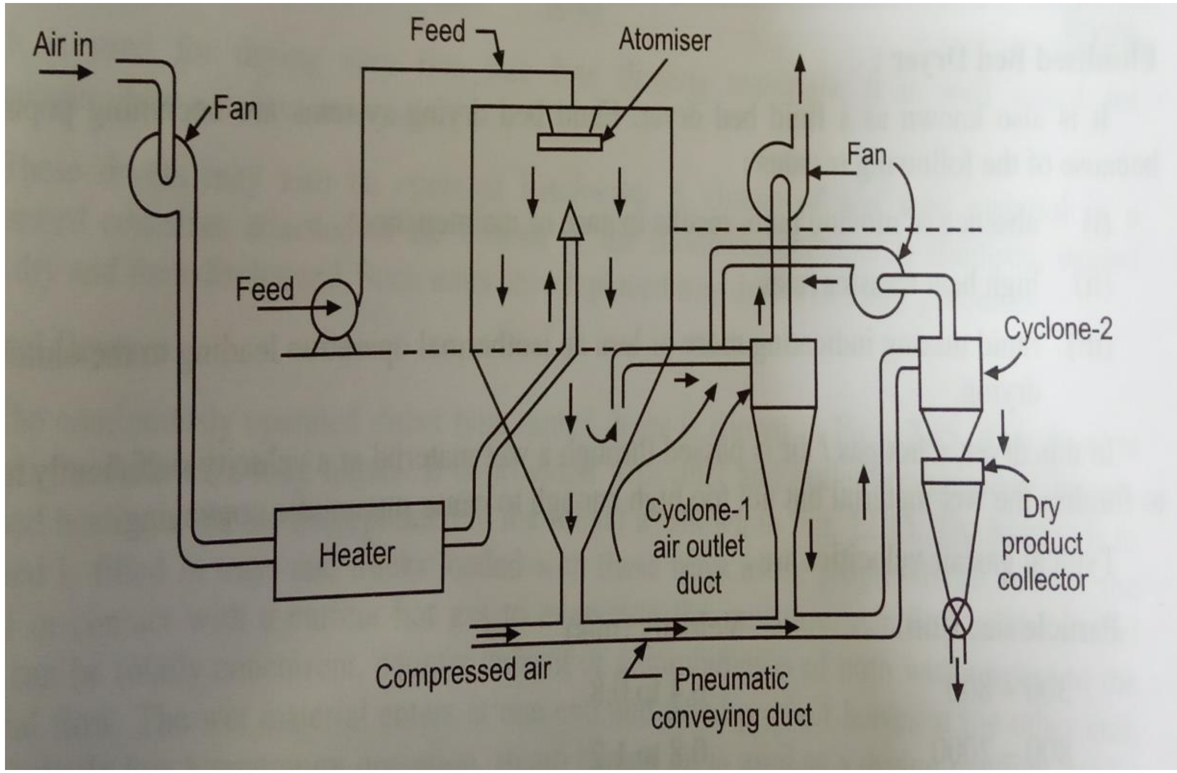
- Continuous direct contact dryer for drying of solutions, slurries and pastes

Consists of a

- Vertical cylindrical with short conical bottom (drying chamber)
- Heater for heating the fresh air sucked by a fan or blower
- Cyclone separators for dust separation and collection
- Pneumatic conveying duct and blowers.

Working of Spray Drier

- Feed is pumped to the top of the drier, disintegrated into small droplets by an atomiser
- Fresh air (in large quantity) taken in a fan, heated in a heater and fed below the atomiser in the drying chamber
- As surface area of drops is very large, liquid portion of these drops rapidly evaporate
- completely dried before touching the bottom of the chamber
- Dried product (powder form) is then conveyed to a cyclone dust collector -2 by a stream of ir
- Major portion of air is taken out through the air outlet duct, which contains dust and is send to cyclone 1
- Solids collected by cyclone 1 are fed to a pneumatic conveying duct
- Air leaving cyclone 2 may contain some dust and further sent to cyclone1 for further separation by fan
- Air from cyclone 1 is thrown out to the atmosphere by a blower
- Dried product is collected in a dry product collector



ADVANTAGES

- Very short drying times (2- 20s)
- Handle heat sensitive products
- Rapid dehydration
- Relatively low operating costs , particularly in large capacity units

DISADVANTAGES

- Relatively large units
- Maintenance of atomiser
- Inefficient in energy usage

Applications

Used for products such as milk powder, detergents, dyes, pharmaceuticals etc.

Liquid –liquid Extraction

- Separation of components of a liquid mixture by treatment with a solvent in which one or more of the desired constituents is preferentially soluble .
- Also termed as solvent extraction
- Utilizes the differences in solubility of the constituents/ components to effect a separation

Extraction process consists of

- contacting the feed with a solvent
- Separation of resulting phases
- Recovery of solvents from each phase

Liquid-Liquid Extraction

Feed – Solution which is to be extracted

Solvent – Liquid with which the feed is contacted for the extraction of solute

Extract – Solvent rich product of the operation, containing the extracted solute

Raffinate – Solvent lean, residual liquid solution from which solute is removed

Mixer Settler

- Single – stage extraction device

Mixer settler consists of

✓ Vertical vessel containing a turbine or propeller agitator

✓ Charging nozzles at the top, discharge connection at the bottom

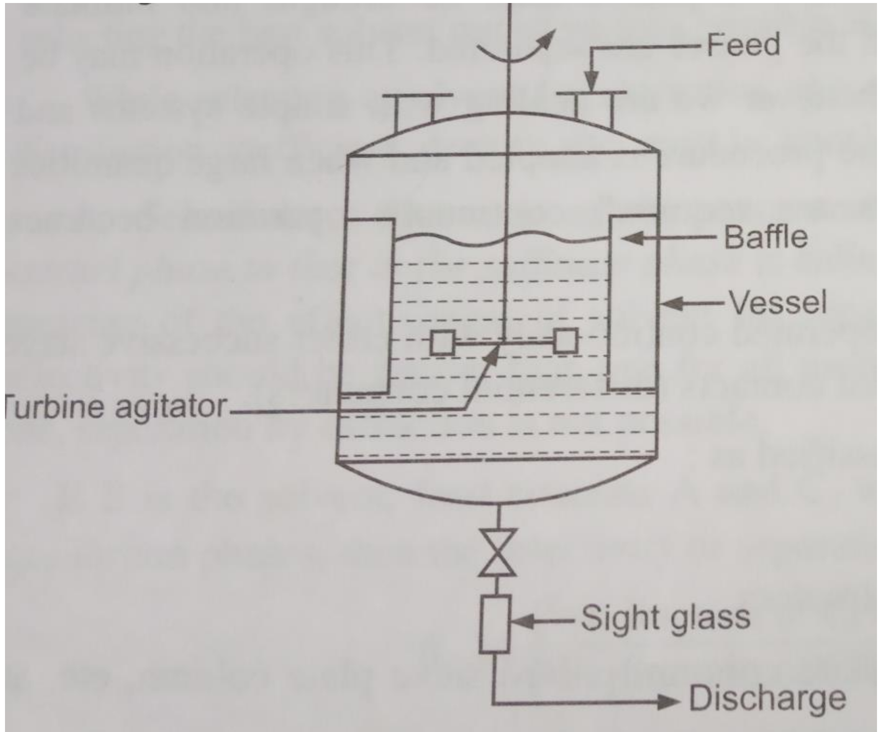
✓Feed to be extracted is taken in agitated vessel, required amount of solvent added

✓Whole mass agitated for a predetermined time

✓Agitation stopped at the end of mixing cycle,

✓Settling is applied for phase separation

✓Raffinate and extract phases are withdrawn from the bottom into separate receivers

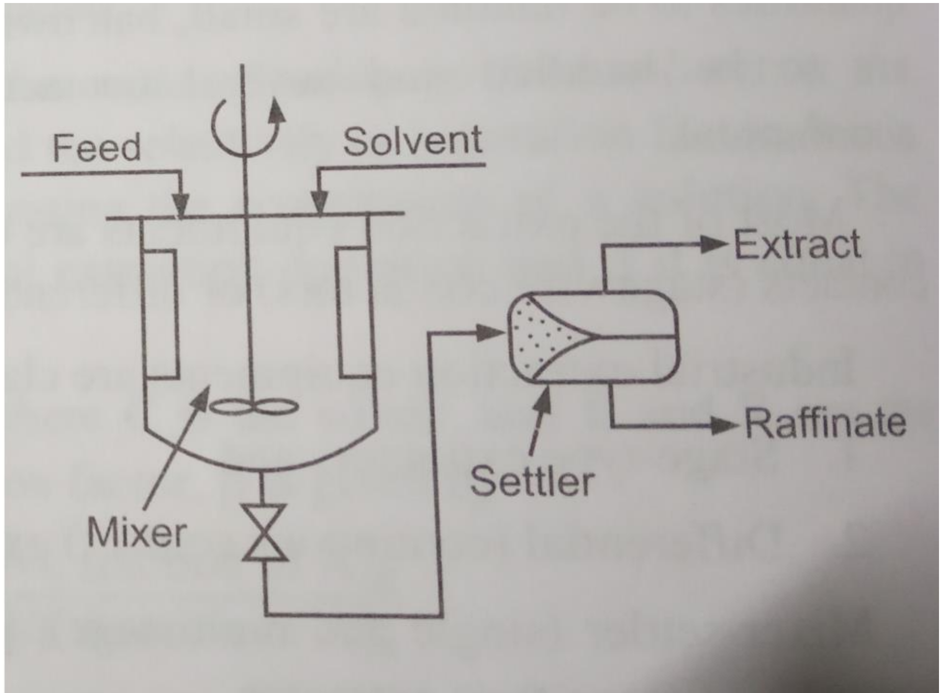


(a) Mixer settler for batch operation
(Mechanically agitated vessel)

Mixer Settler

For continuous extraction operation

- ✓ Mixer ad settler are separate units
- ✓ Mixer is a small baffled agitated tank provided with inlet-outlet connection
- ✓ Settler is a continuous gravity decanter
- ✓ Here two phases are continuously in contact with each other in the mixer under agitation before flowing to settler for phase separation



(b) Continuous single-stage Mixer-settler

Advantages: high stage efficiency, good flexibility, capacity to handle liquids of high viscosity, high capacity

These units are used in petrochemical, fertilisers and metallurgical industries.

LEACHING

Leaching is a process of mass transfer that occurs by extracting a substance from a solid material that has come into contact with a liquid/ solvent. The desired component diffuses into the solvent from its natural solid form.

Leaching occurs through the following steps:

- Solvent is transferred from the bulk solution to the surface of the solid.
- Solvent penetrates or diffuses into the solid.
- Solute dissolves from the solid into the solvent.
- Solute diffuses through the mixture to the surface of the solid.
- Solute is transferred to the bulk solution.

APPLICATIONS OF LEACHING

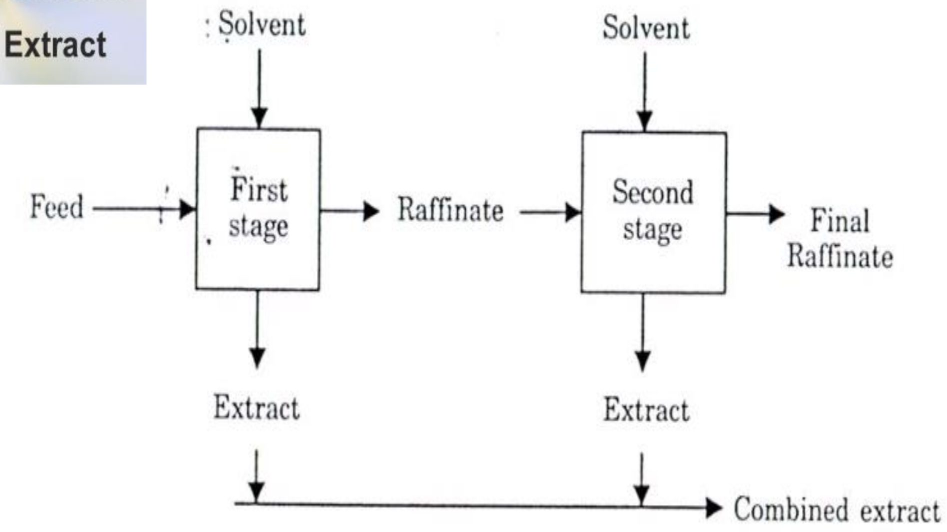
- ✓ Metals industry for removing mineral from ores (acid solvents)
- ✓ Sugar industry for removing sugar from beets (water is solvent)
- ✓ Oilseeds industry for removing oil from soybeans, etc. (hexane or similar organic solvents)

BATCH LEACHING PROCESS

It can be single stage or multiple stage.

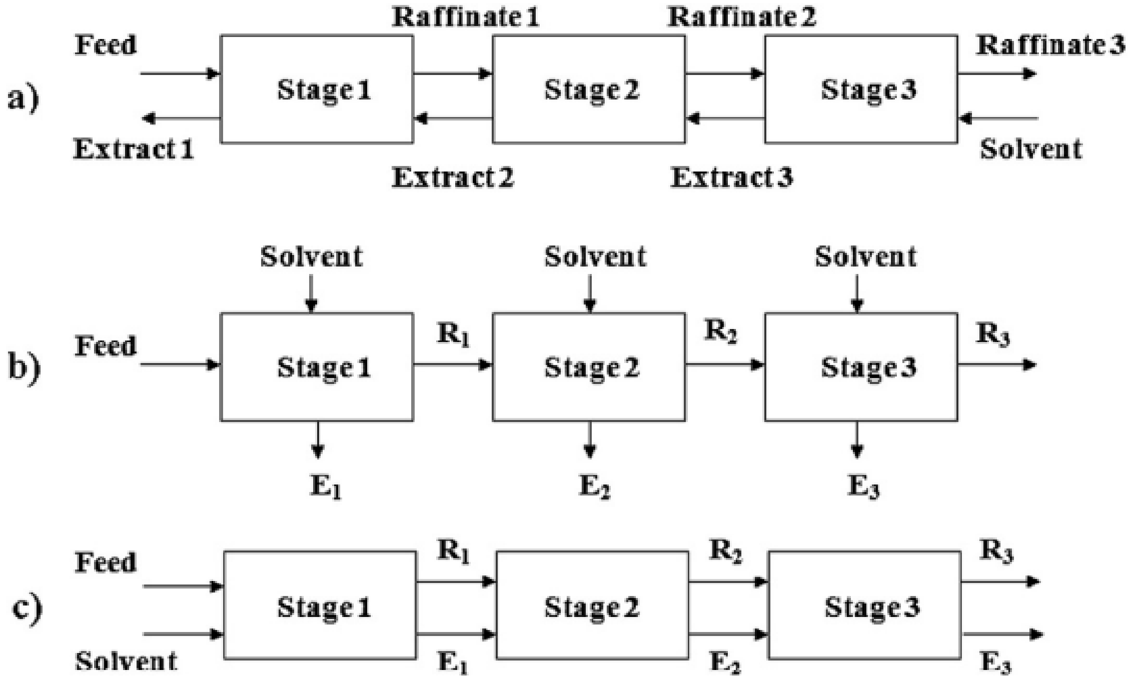
- In the single stage batch process, the solvent and solution are mixed together and then allowed to separate into two phases – the extract F containing the required solute in the added solvent and the raffinate R, the weaker solution with some associated solvent. With this simple arrangement mixing and separation occur in the same vessel.

- Batch extraction in multiple stage



CONTINUOUS LEACHING PROCESS

- Using continuous equipment in which the solid and liquid are both moved mechanically, and by the use of a series of leach tanks and the counter current flow of solvent through the tanks in reverse order to the flow of solid.



Three different ways of connecting in liquid–liquid extraction: (a) counter-current; (b) cross-current and (c) co-current.

Boll man extractor

- Used for the recovery of additional oil from the residues obtained after mechanical pressing of solids.
- Consists of a vapour tight vertical chamber in which a series of perforated baskets are attached to a chain conveyor
- Baskets are provided with perforations at the bottom
- Dry flakes or solids are added at the upper right side to a perforated basket in a closed casing.
- As the baskets on the right descend, they are leached by a dilute solution of oil in solvent called half miscella.
- Half Miscella is the intermediate solvent containing some extracted oil and some small solid particles.

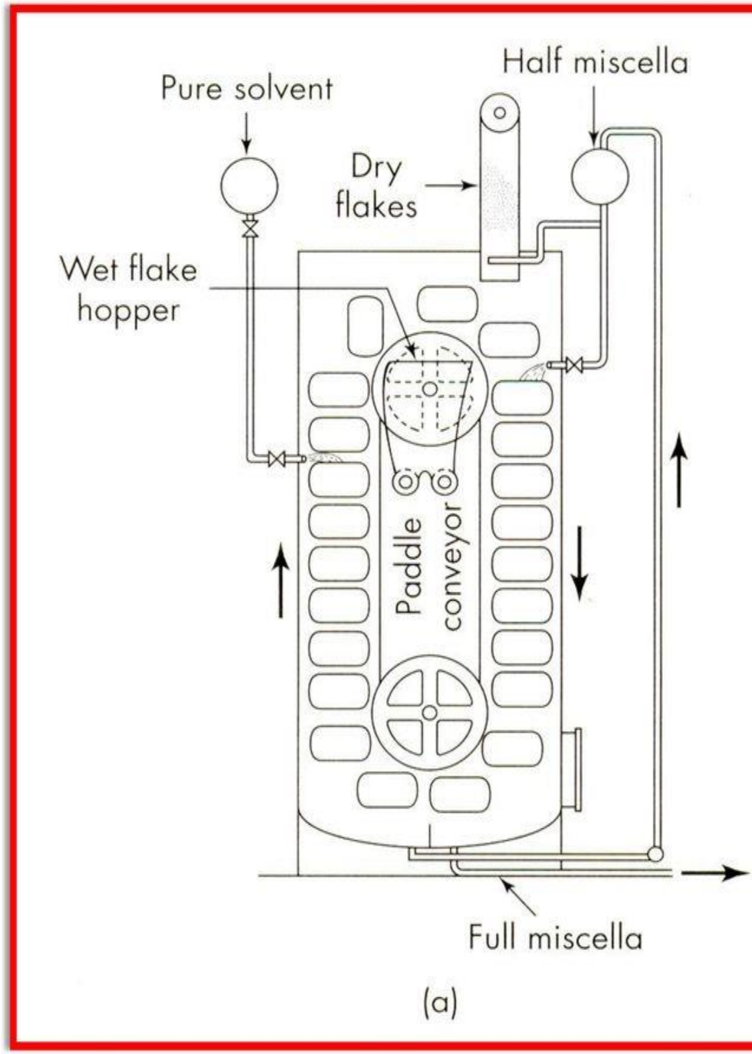


Fig. 23.1 (a) Bollman extractor

Boll man extractor

- As the solids and solvent flow co-currently down the right hand side of the machine, the solvent extracts more oil.
- Fine solids are filtered out of the solvent, so that the clean full miscella can be pumped from the outlet provided at the right hand bottom.
- As these partially extracted solids rise through the left hand side of the machine a stream of pure solvent is sprayed on them to obtain a dilute solution of the oil (half miscella) at the bottom of the chamber.
- Pure solvent percolates counter-currently through them and collects in the left hand sump which is then passed to the Half Miscella storage tank.
- Fully extracted solids are then dumped from the baskets at the top of the elevator to the hoppers from which they are removed by Screw Conveyors

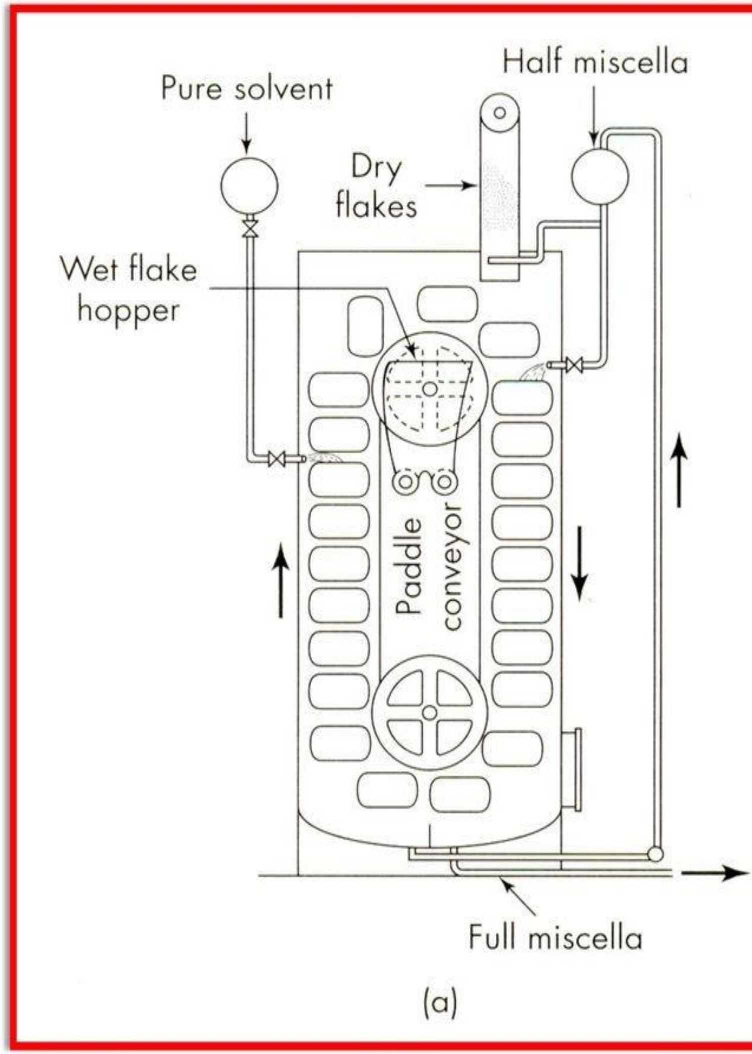


Fig. 23.1 (a) Bollman extractor