

1. (a) What is the purpose of material and energy balance?

- The purpose of material and energy balance is to account for all the material and energy entering, leaving, accumulating, or being consumed/generated within a system.
- It is based on the fundamental principles of conservation of mass and conservation of energy.
- Material balance helps in determining the quantities of raw materials needed, products formed, and waste generated in a process. It is crucial for process design, optimization, and control.
- Energy balance helps in understanding the energy requirements of a process, identifying areas for energy conservation, and designing heat exchange equipment. It is essential for optimizing energy efficiency and reducing operating costs.
- Together, they provide a comprehensive understanding of a process, enabling engineers to design, operate, and troubleshoot chemical and physical processes efficiently and safely.

2. (b) Discuss the role of diffusion in mass transfer.

- Diffusion is a fundamental mechanism in mass transfer, which is the net movement of mass from one location, usually a region of high concentration, to another location, usually a region of lower concentration.
- In diffusion, individual molecules move randomly, but there is a net movement from an area of higher concentration to an area of lower concentration, driven by the concentration gradient.
- It is a spontaneous process that aims to equalize concentration differences within a system.
- Diffusion plays a crucial role in various mass transfer operations such as absorption, desorption, distillation, extraction, drying, and membrane separation.

- For example, in gas absorption, the solute gas diffuses from the gas phase into the liquid phase. In drying, water vapor diffuses from the wet solid surface into the surrounding air.
- The rate of diffusion is described by Fick's laws and is influenced by factors such as temperature, pressure, and the properties of the diffusing substance and the medium.

3. (c) Write short note on air cooled heat exchanger.

- An air-cooled heat exchanger (ACHE), also known as a fin-fan cooler or air fin cooler, is a type of heat exchanger that uses ambient air as the cooling medium to dissipate heat from a hot process fluid.
- It consists of finned tubes through which the hot fluid flows, and a fan that forces ambient air across these finned tubes. The fins increase the heat transfer surface area, enhancing the heat exchange process.
- ACHEs are commonly used in industries where water is scarce, expensive, or poses environmental concerns, as they eliminate the need for cooling water.
- They are prevalent in petrochemical plants, refineries, power plants, and gas processing facilities for cooling various process streams, such as steam condensers, intercoolers, and aftercoolers.
- Advantages include reduced water consumption, lower operating costs (no water treatment or disposal), and environmental benefits.
- Disadvantages include larger footprint compared to water-cooled exchangers, sensitivity to ambient air temperature fluctuations, and higher power consumption for fans.

4. (d) Discuss Schmidt number and its significance.

- Schmidt number (Sc) is a dimensionless number defined as the ratio of momentum diffusivity (kinematic viscosity) to mass diffusivity. It is given by the formula: $Sc = \frac{\nu}{D_{AB}} = \frac{\mu}{\rho D_{AB}}$, where ν is the kinematic

viscosity, D_{AB} is the mass diffusivity, μ is the dynamic viscosity, and ρ is the density.

○ Significance:

- It relates the relative thickness of the momentum boundary layer and the concentration (mass transfer) boundary layer.
- A Schmidt number close to 1 indicates that the momentum and mass diffusion rates are comparable, meaning the velocity and concentration profiles are similar.
- For gases, the Schmidt number is typically around 0.5 to 2, indicating that momentum and mass diffuse at similar rates.
- For liquids, the Schmidt number can be much higher (hundreds or thousands), implying that momentum diffuses much faster than mass. This means that mass transfer is often the rate-limiting step in liquid-phase processes.
- It is an important parameter in mass transfer calculations, particularly in convective mass transfer, as it helps in correlating mass transfer coefficients with fluid flow characteristics.
- It is analogous to the Prandtl number in heat transfer, which relates momentum diffusivity to thermal diffusivity.

5. (e) Explain Reynolds number.

- Reynolds number (Re) is a dimensionless quantity that helps predict flow patterns in different fluid flow situations. It is defined as the ratio of inertial forces to viscous forces within a fluid.
- The formula for Reynolds number is: $Re = \frac{\rho v L}{\mu} = \frac{v L}{\nu}$, where ρ is the fluid density, v is the characteristic flow velocity, L is the characteristic linear dimension (e.g., pipe diameter), μ is the dynamic viscosity of the fluid, and ν is the kinematic viscosity ($\nu = \mu/\rho$).

○ Significance:

- The Reynolds number is a crucial parameter for determining whether a fluid flow is laminar, transitional, or turbulent.
- Laminar flow (low Reynolds number, typically $Re < 2100$ for flow in a pipe) is characterized by smooth, orderly, and predictable fluid motion in layers, with little or no mixing between layers.
- Turbulent flow (high Reynolds number, typically $Re > 4000$ for flow in a pipe) is characterized by chaotic, irregular, and unpredictable fluid motion with significant mixing.
- Transitional flow occurs at intermediate Reynolds numbers (between 2100 and 4000 for pipe flow), where the flow can fluctuate between laminar and turbulent states.
- It is widely used in engineering to design and analyze fluid flow systems, predict pressure drop, heat transfer, and mass transfer characteristics.
- For example, in pipe flow, it helps engineers select appropriate pump sizes and pipe diameters to achieve desired flow conditions and minimize energy losses.

6. (a) Write short note on azeotropic distillation.

- Azeotropic distillation is a specialized distillation technique used to separate components of a liquid mixture that form an azeotrope. An azeotrope is a mixture of two or more liquids that boils at a constant temperature and has the same vapor-phase composition as its liquid-phase composition. This means that traditional distillation cannot separate the components of an azeotrope by simple boiling.
- In azeotropic distillation, a third component, known as an entrainer or azeotropic agent, is added to the mixture. The entrainer forms a new, lower-boiling azeotrope with one of the original components, which can then be separated by conventional distillation.

- The entrainer is carefully chosen such that it forms an azeotrope with one of the components that is easily separable from the other component(s). For example, ethanol and water form an azeotrope at approximately 95.6% ethanol by weight. Benzene or cyclohexane can be used as an entrainer to break this azeotrope. Benzene forms a ternary azeotrope with ethanol and water that boils at a lower temperature, allowing the removal of water.
 - After the separation, the entrainer is typically recovered and recycled back into the process. This method is widely used in industries for separating mixtures that are difficult or impossible to separate by conventional distillation, such as ethanol-water, acetic acid-water, and acetone-methanol.
7. (b) The gas acetylene is produced according to the following reaction by treating calcium carbide with water: $\text{CaC}_2 + 2\text{H}_2\text{O} \rightarrow \text{C}_2\text{H}_2 + \text{Ca(OH)}_2$
 Calculate the number of hours of service that can be derived from 1.0 kg of carbide in an acetylene lamp burning 60 litres of gas per hour at a temperature of 20°C and a pressure of 740 mm Hg.
- Given reaction: $\text{CaC}_2 + 2\text{H}_2\text{O} \rightarrow \text{C}_2\text{H}_2 + \text{Ca(OH)}_2$
 - Molecular weight of $\text{CaC}_2 = 40.08 \text{ (Ca)} + 2 * 12.01 \text{ (C)} = 64.1 \text{ g/mol}$
 - Molecular weight of $\text{C}_2\text{H}_2 = 2 * 12.01 \text{ (C)} + 2 * 1.008 \text{ (H)} = 26.04 \text{ g/mol}$
 - From the stoichiometry, 1 mole of CaC_2 produces 1 mole of C_2H_2 .
 - Moles of CaC_2 in 1.0 kg (1000 g) = $1000 \text{ g} / 64.1 \text{ g/mol} = 15.60 \text{ moles of CaC}_2$
 - Therefore, moles of C_2H_2 produced = 15.60 moles
 - Now, we need to find the volume of C_2H_2 produced at given conditions using the ideal gas law: $PV = nRT$
 - $P = 740 \text{ mm Hg} = 740 / 760 \text{ atm} = 0.9737 \text{ atm}$
 - $V = ?$

- $n = 15.60$ moles
 - $R = 0.08206 \text{ L}\cdot\text{atm}/(\text{mol}\cdot\text{K})$
 - $T = 20^\circ\text{C} = 20 + 273.15 = 293.15 \text{ K}$
 - $V = (nRT) / P = (15.60 \text{ mol} * 0.08206 \text{ L}\cdot\text{atm}/(\text{mol}\cdot\text{K}) * 293.15 \text{ K}) / 0.9737 \text{ atm}$
 - $V = 384.88 \text{ L}$
 - The lamp burns 60 litres of gas per hour.
 - Number of hours of service = Total volume of C_2H_2 produced / Rate of burning
 - Number of hours of service = $384.88 \text{ L} / 60 \text{ L/hour} = 6.41 \text{ hours}$
8. (c) What is size reduction? Discuss the working principal of ball-mill and its construction.
- What is size reduction?
 - Size reduction, also known as comminution or grinding, is a unit operation in which larger solid particles are broken down into smaller particles.
 - The primary aim of size reduction is to increase the surface area of the material, which can enhance reaction rates, improve extraction efficiency, facilitate mixing, and improve flow properties.
 - It is a crucial step in many industries, including mineral processing, pharmaceuticals, food processing, chemical manufacturing, and ceramics.
 - Size reduction can be achieved through various mechanisms such as compression, impact, attrition (rubbing), and cutting.
 - Discuss the working Principle of ball-mill and its construction.
 - Working Principle of Ball Mill:

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- A ball mill operates on the principle of impact and attrition. As the mill rotates, the grinding media (balls) are lifted along the inside wall of the mill due to centrifugal force and then fall back down, impacting the material.
 - The material also undergoes attrition as the balls roll over each other and against the mill lining.
 - The rotation speed is critical: if it's too slow, the balls will slide; if it's too fast (above critical speed), the balls will centrifuge against the wall and not fall, leading to inefficient grinding.
 - The critical speed is the speed at which the centrifugal force on the balls is just enough to hold them against the mill wall. Ball mills are typically operated at a speed lower than the critical speed, usually around 65-80% of the critical speed.
- Construction of Ball Mill:
- A ball mill consists of a cylindrical or conical shell, typically made of steel, which is mounted horizontally on trunnions or rollers and can be rotated.
 - The inside of the shell is lined with wear-resistant materials like manganese steel, rubber, or ceramic, to protect the shell from abrasion by the grinding media and the material being ground. These liners can also have lifters to aid in lifting the grinding media.
 - The mill is partially filled (typically 30-50% of its volume) with grinding media, which can be steel balls, ceramic balls, or flint pebbles. The size and type of grinding media depend on the material being ground and the desired product fineness.

- The material to be ground (feed) is introduced continuously into the mill through one of the hollow trunnions or an inlet chute.
- As the mill rotates, the grinding media tumble and cascade, grinding the material.
- The finely ground product exits the mill through the opposite trunnion or an outlet chute, often through a discharge grate or screen to control particle size.
- Ball mills can be operated in batch or continuous mode and can be wet or dry mills.

9. (a) Discuss the Henry law and its limitation in details.

○ Henry's Law:

- Henry's Law states that at a constant temperature, the amount of a given gas that dissolves in a given type and volume of liquid is directly proportional to the partial pressure of that gas in equilibrium with the liquid.
- Mathematically, it can be expressed as: $P_A = H \cdot x_A$ or $P_A = H' \cdot C_A$
 - Where P_A is the partial pressure of component A in the gas phase.
 - x_A is the mole fraction of component A in the liquid phase.
 - C_A is the concentration of component A in the liquid phase.
 - H and H' are Henry's Law constants, which are specific to the solute-solvent pair and temperature.
- In simpler terms, the higher the partial pressure of a gas above a liquid, the more of that gas will dissolve in the liquid. This law

is crucial for understanding gas solubility in liquids, which is vital in various processes like gas absorption, carbonated beverages, and environmental engineering (e.g., oxygen dissolution in water).

○ Limitations of Henry's Law:

- **Low Concentration/Dilute Solutions:** Henry's Law is strictly applicable only for dilute solutions where the solute-solvent interactions are not significantly altered by the presence of the solute. As the concentration of the dissolved gas increases, deviations from linearity occur.
- **Low Pressure:** The law holds true for gases at low partial pressures. At very high pressures, the behavior of the gas deviates significantly from ideal gas behavior, and its solubility no longer follows a simple linear relationship with partial pressure.
- **No Chemical Reaction:** Henry's Law is valid only when the gas does not react chemically with the solvent. If a chemical reaction occurs (e.g., CO_2 dissolving in water to form carbonic acid), the amount of gas dissolved will be higher than predicted by Henry's Law, as the dissolved gas is consumed by the reaction, shifting the equilibrium.
- **Constant Temperature:** The Henry's Law constant is highly dependent on temperature. The law applies only at a constant temperature. An increase in temperature generally decreases the solubility of gases in liquids.
- **Ideal Gas Behavior:** It implicitly assumes that the gas phase behaves ideally. Deviations from ideal gas behavior at high pressures or low temperatures can lead to inaccuracies.
- **Limited to Gases:** The law is specifically for the solubility of gases in liquids. It does not apply to the solubility of solids or liquids in other liquids.

10.(b) What is mass transfer phenomenon? Discuss the "Two film theory" in details.

- What is mass transfer phenomenon?
 - Mass transfer is the net movement of mass from one location to another due to a concentration difference (gradient).
 - It is a fundamental transport phenomenon, alongside heat transfer and momentum transfer.
 - Mass transfer occurs whenever there is a difference in the chemical potential or concentration of a component between two phases or within the same phase.
 - The driving force for mass transfer is the concentration gradient, and the movement continues until equilibrium is reached and the concentration becomes uniform.
 - Mass transfer operations are crucial in chemical engineering for separating mixtures (e.g., distillation, absorption, extraction), purifying substances, and promoting chemical reactions.
- Discuss the "Two film theory" in details.
 - The "Two Film Theory," proposed by Whitman and Lewis, is a conceptual model used to describe mass transfer across an interface between two immiscible phases (e.g., gas-liquid, liquid-liquid).
 - It postulates that all resistance to mass transfer is concentrated in two thin, stagnant fluid films on either side of the interface, one in each phase.
 - Within these films, mass transfer occurs primarily by molecular diffusion, driven by the concentration gradient.
 - Outside these films, in the bulk phases, the fluid is assumed to be well-mixed, and mass transfer occurs primarily by convection, so there is no concentration gradient.

- At the interface itself, it is assumed that thermodynamic equilibrium exists, meaning there is no resistance to mass transfer across the interface and the concentrations are in equilibrium.
- Detailed Explanation:
 - Consider mass transfer of a component A from a gas phase to a liquid phase.
 - **Gas Film:** As component A moves from the bulk gas phase towards the interface, it first encounters a stagnant gas film. The concentration of A decreases continuously through this film from the bulk gas concentration (C_{AG}) to the interfacial gas concentration (C_{Ai}). The mass transfer within this film is governed by molecular diffusion.
 - **Liquid Film:** At the interface, the component A dissolves into the liquid phase. It then encounters a stagnant liquid film, through which it travels from the interfacial liquid concentration (C_{ALi}) to the bulk liquid concentration (C_{AL}). The mass transfer within this film is also governed by molecular diffusion.
 - **Interfacial Equilibrium:** The key assumption is that at the interface, the gas and liquid phases are in equilibrium. This means that C_{Ai} and C_{ALi} are related by an equilibrium relationship, such as Henry's Law for gas-liquid systems ($P_A = H \cdot C_A$) or a partition coefficient for liquid-liquid systems.
 - **Mass Transfer Rate:** The overall mass transfer rate is determined by the resistances in both films. If one film offers significantly more resistance than the other, it is considered the "rate-limiting" or "controlling" film.
 - The flux of component A (N_A) can be expressed as:

- $N_A = k_G(P_G - P_{Gi})$ (in the gas film)
- $N_A = k_L(C_{Li} - C_L)$ (in the liquid film)
- Where k_G and k_L are individual mass transfer coefficients for the gas and liquid films, respectively, and P and C represent partial pressures and concentrations.
- Overall mass transfer coefficients (K_G based on gas phase driving force, K_L based on liquid phase driving force) can also be defined, which combine the resistances of both films.
- **Overall resistance = Resistance in gas film + Resistance in liquid film.**
- The two-film theory provides a conceptual framework for understanding and modeling mass transfer processes, although in reality, the "films" are not truly stagnant but rather regions of high concentration gradient. It is widely used for practical calculations and design of mass transfer equipment.

11.(c) Dry methane is burned with dry air (both are initially at 25°C). The flame temperature is 1297°C. If complete combustion is assumed, how much excess air is to be used? Data: Heat of reaction, $\Delta H_R = -0.2 \times 10^6$ cal. C_p for $\text{CO}_2 = 12.37$ cal/mol°C C_p for $\text{H}_2\text{O} = 9.60$ cal/mol°C C_p for $\text{N}_2 = 7.68$ cal/mol°C C_p for air = 7.74 cal/mol°C

- This is an energy balance problem involving combustion. We need to apply the first law of thermodynamics, considering the enthalpy change.
- Basis: 1 mole of Methane (CH_4)
- Complete combustion reaction: $\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$
- Air composition (approximate): 21% O_2 , 79% N_2

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- Required O_2 for 1 mole $CH_4 = 2$ moles
- Required air for 1 mole $CH_4 = 2$ moles $O_2 * (100 \text{ moles air} / 21 \text{ moles } O_2) = 9.524$ moles of air
- Moles of N_2 in required air = $9.524 \text{ moles air} * 0.79 = 7.524$ moles N_2
- Heat of reaction (ΔH_R) = $-0.2 \times 10^6 \text{ cal} = -200,000 \text{ cal/mol } CH_4$
- Let 'x' be the moles of excess air used per mole of theoretical air.
- Total air supplied = $(1 + x) * 9.524$ moles
- Total O_2 supplied = $(1 + x) * 2$ moles
- Excess $O_2 = x * 2$ moles
- Total N_2 supplied = $(1 + x) * 7.524$ moles
- Products of combustion:
 - $CO_2 = 1$ mole
 - $H_2O = 2$ moles
 - N_2 (from air) = $(1 + x) * 7.524$ moles
 - Excess $O_2 = x * 2$ moles
- Energy Balance: Heat of reaction + Sensible heat of reactants = Sensible heat of products
- Assuming reactants are at $25^\circ C$ (reference temperature), their sensible heat is 0.
- So, $\Delta H_R = \text{Sensible heat of products at } 1297^\circ C \text{ (relative to } 25^\circ C)$
- Sensible heat (ΔH) = $n * C_{p_avg} * \Delta T$, where $\Delta T = T_{final} - T_{initial} = 1297^\circ C - 25^\circ C = 1272^\circ C$
- Sensible heat of products:
 - $\Delta H_{CO_2} = 1 \text{ mol} * 12.37 \text{ cal/(mol}^\circ C) * 1272^\circ C = 15739.44 \text{ cal}$

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- $\Delta H_{\text{H}_2\text{O}} = 2 \text{ mol} * 9.60 \text{ cal}/(\text{mol}^\circ\text{C}) * 1272^\circ\text{C} = 24422.4 \text{ cal}$
- $\Delta H_{\text{N}_2} = (1 + x) * 7.524 \text{ mol} * 7.68 \text{ cal}/(\text{mol}^\circ\text{C}) * 1272^\circ\text{C} = (1 + x) * 73444.69 \text{ cal}$
- $\Delta H_{\text{excess O}_2} = x * 2 \text{ mol} * 7.74 \text{ cal}/(\text{mol}^\circ\text{C}) * 1272^\circ\text{C} = x * 19688.16 \text{ cal}$ (Assuming C_p for O_2 is similar to air or N_2)
- Total sensible heat of products = $15739.44 + 24422.4 + (1 + x) * 73444.69 + x * 19688.16$
- Total sensible heat = $40161.84 + 73444.69 + 73444.69x + 19688.16x$
- Total sensible heat = $113606.53 + 93132.85x$
- Now, apply the energy balance: $-200,000 \text{ cal} = 113606.53 + 93132.85x$
- $-200,000 - 113606.53 = 93132.85x$
- $-313606.53 = 93132.85x$
- $x = -313606.53 / 93132.85 = -3.367$
- There seems to be an issue here. The flame temperature is given as 1297°C and heat of reaction is negative (exothermic). This means the heat released by the reaction is used to raise the temperature of the products. So, the sign convention should be: Heat released by reaction = Sensible heat gained by products.
- $|\Delta H_R| = \sum n_p C_{p,p} \Delta T$
- $200,000 \text{ cal} = 113606.53 + 93132.85x$
- $200,000 - 113606.53 = 93132.85x$
- $86393.47 = 93132.85x$
- $x = 86393.47 / 93132.85 = 0.9276$
- Percentage excess air = $x * 100\%$

- Percentage excess air = $0.9276 * 100\% = 92.76\%$
- Therefore, approximately 92.76% excess air is used.

12.(a) What is an adsorption isotherm? Discuss the various applications of adsorption in details.

- What is an adsorption isotherm?
 - An adsorption isotherm is a graph or mathematical equation that describes the relationship between the amount of adsorbate adsorbed on the surface of an adsorbent and the equilibrium concentration or partial pressure of the adsorbate in the bulk fluid phase (gas or liquid) at a constant temperature.
 - It essentially shows how much material is adsorbed at different concentrations/pressures when the system has reached equilibrium.
 - Common types of adsorption isotherms include Langmuir, Freundlich, BET, and Temkin isotherms, each based on different assumptions about the adsorption process and surface properties.
 - Adsorption isotherms are crucial for understanding the adsorption mechanism, predicting adsorption capacity, and designing adsorption processes.
- Discuss the various applications of adsorption in details.
 - Adsorption is a widely used separation process in various industries due to its effectiveness in removing trace impurities or recovering valuable components.
 - **Gas Purification and Separation:**
 - **Air Separation:** Production of oxygen and nitrogen from air using Pressure Swing Adsorption (PSA) or Vacuum Swing Adsorption (VSA) with zeolites or carbon molecular sieves.

- **Natural Gas Sweetening:** Removal of acid gases like H_2S and CO_2 from natural gas using molecular sieves.
 - **Hydrogen Purification:** Separation of hydrogen from reformer off-gas or synthesis gas.
 - **Odor Removal:** Activated carbon filters are extensively used to remove volatile organic compounds (VOCs) and unpleasant odors from air streams in industrial and domestic settings.
 - **Drying of Gases:** Adsorbents like silica gel, alumina, and molecular sieves are used to remove moisture from air and other gases to prevent corrosion and improve process efficiency.
- **Water and Wastewater Treatment:**
- **Drinking Water Purification:** Activated carbon is used to remove dissolved organic pollutants, pesticides, herbicides, chlorine, and taste/odor-causing compounds from drinking water.
 - **Industrial Wastewater Treatment:** Removal of heavy metals, dyes, phenols, and other toxic organic compounds from industrial effluents.
 - **Groundwater Remediation:** Adsorption can be used to treat contaminated groundwater by removing specific pollutants.
- **Chemical and Pharmaceutical Industries:**
- **Decolorization:** Activated carbon is used to remove colored impurities from sugar syrups, edible oils, and pharmaceutical solutions.

- **Catalysis:** Adsorbents act as catalyst supports (e.g., zeolites in catalytic cracking), providing a large surface area for catalytic reactions.
- **Chromatography:** Adsorption is the fundamental principle behind various chromatographic techniques (e.g., gas chromatography, liquid chromatography) used for separating and analyzing mixtures.
- **Drug Purification:** Used in the purification and separation of active pharmaceutical ingredients.
- **Environmental Applications:**
 - **Pollution Control:** Removal of SO_x, NO_x, and mercury from flue gases.
 - **Oil Spill Cleanup:** Adsorbents can be used to absorb oil from water surfaces.
- **Other Applications:**
 - **Desiccants:** Adsorbents like silica gel are used in packaging to protect moisture-sensitive products.
 - **Refrigeration:** Adsorption refrigeration systems use the adsorption/desorption cycle to produce cooling, offering an environmentally friendly alternative.
 - **Medical Applications:** Activated carbon is used in emergency medicine to absorb toxins in cases of poisoning.

13.(b) What is drying? Illustrate the different stages of drying of moist solid.

- What is drying?
 - Drying is a mass transfer operation that involves the removal of a volatile component (usually water) from a solid, semi-solid, or liquid by evaporation into a surrounding gas phase.

- The objective of drying is typically to reduce the moisture content to a specified level, which can improve product stability, extend shelf life, reduce transportation costs, or prepare the material for further processing.
- It is different from evaporation, which removes larger quantities of liquid by boiling, whereas drying usually refers to the removal of relatively small amounts of water at temperatures below its boiling point.
- Illustrate the different stages of drying of moist solid.
 - The drying of a moist solid is generally characterized by a drying rate curve, which plots the drying rate (mass of moisture removed per unit time per unit area) against the moisture content of the solid. This curve typically shows several distinct stages:
 - **1. Constant Rate Period (CRP):**
 - In this initial stage, the surface of the solid is completely saturated with moisture, behaving like a free liquid surface.
 - Evaporation occurs from this saturated surface, and the rate of drying is constant and independent of the moisture content of the solid.
 - The rate of mass transfer is controlled by the rate of heat transfer to the surface and the rate of vapor diffusion from the surface into the bulk air.
 - The temperature of the solid remains constant at the wet-bulb temperature of the drying air.
 - This period continues until the critical moisture content (X_c) is reached, at which point the surface is no longer fully saturated, and dry spots begin to appear.

▪ **2. First Falling Rate Period (FRP-I):**

- After the critical moisture content, dry spots appear on the surface, and the area of the exposed liquid surface decreases progressively.
- The rate of drying begins to fall because the rate of evaporation is now limited by the rate at which moisture can diffuse from the interior of the solid to the surface.
- The rate of mass transfer is still largely controlled by external conditions (air velocity, temperature, humidity), but internal diffusion becomes increasingly important.
- The surface temperature may begin to rise slightly above the wet-bulb temperature.
- This period continues until the entire surface is dry, and internal diffusion becomes the sole mechanism for moisture transport.

▪ **3. Second Falling Rate Period (FRP-II):**

- In this stage, the surface of the solid is completely dry, and the plane of evaporation recedes into the interior of the solid.
- Moisture movement to the surface occurs solely by internal diffusion (liquid diffusion, capillary flow, vapor diffusion, or a combination).
- The rate of drying is entirely controlled by the internal moisture movement mechanisms and falls sharply as the moisture content decreases.
- The temperature of the solid approaches the dry-bulb temperature of the drying air.

- This period continues until the equilibrium moisture content (X^*) is reached, where the solid is in moisture equilibrium with the drying air, and the net drying rate becomes zero.
- **Equilibrium Moisture Content (X^*):** This is the final moisture content that the solid will reach if left in contact with the drying air for an infinitely long time. It depends on the relative humidity and temperature of the air, and the nature of the solid.

14.(c) Discuss different types of unit operation used in polymer synthesis industry.

- The polymer synthesis industry involves a series of unit operations to transform monomers into polymers and then process these polymers into desired forms. Some key unit operations include:
 - **Reaction (Polymerization):**
 - This is the core unit operation where monomers are chemically reacted to form long polymer chains.
 - Types include bulk polymerization, solution polymerization, suspension polymerization, emulsion polymerization, and gas-phase polymerization. Each type involves specific reactor designs (e.g., stirred tank reactors, loop reactors, fluidized bed reactors) and conditions (temperature, pressure, initiators, catalysts).
 - **Heat Transfer:**
 - Polymerization reactions are often highly exothermic, requiring efficient heat removal to control temperature and prevent runaway reactions.
 - Heat exchangers (shell-and-tube, plate-and-frame) are used to remove heat during polymerization or to cool/heat polymer melts/solutions.

- Jacketed reactors and internal cooling coils are common in polymerization reactors.

▪ **Mixing and Agitation:**

- Essential for ensuring uniform temperature distribution, dispersing monomers/initiators, promoting reaction homogeneity, and suspending solid particles (in suspension/emulsion polymerization).
- Various types of agitators and mixers are used depending on the viscosity of the polymerizing mixture (e.g., propeller, turbine, anchor, helical ribbon impellers).

▪ **Separation and Purification:**

- **Devolatilization:** Removal of unreacted monomers, solvents, and other volatile components from the polymer product, often using devolatilizing extruders, wiped-film evaporators, or flash tanks.
- **Filtration:** Removal of solid impurities, unreacted catalyst residues, or polymer particles from a liquid stream.
- **Washing:** Removing impurities by washing the polymer slurry or solution with a solvent or water.
- **Drying:** Removal of residual moisture from solid polymer pellets or powders using various dryers (e.g., fluid bed dryers, rotary dryers, vacuum dryers).
- **Centrifugation:** Used to separate polymer solids from liquids, especially in suspension or emulsion polymerization.
- **Distillation/Evaporation:** To recover and recycle solvents or unreacted monomers, or to concentrate polymer solutions.

▪ **Size Reduction (Comminution):**

- Polymer products (e.g., films, sheets, large chunks) may need to be cut or ground into smaller, more manageable forms (pellets, powders) for further processing or packaging.
- Choppers, granulators, and pulverizers are used for this purpose.

▪ **Extrusion and Pelletizing:**

- After polymerization and purification, molten polymers are often extruded through dies to form strands, which are then cut into uniform pellets.
- Extruders (single-screw, twin-screw) are key for melting, mixing, and shaping the polymer. Pelletizers cut the strands into pellets.

▪ **Pumping and Transport:**

- Moving monomers, solvents, catalysts, and polymer solutions/melts throughout the plant.
- Various types of pumps (centrifugal, positive displacement, gear pumps for high viscosity) and conveyors (pneumatic, belt, screw conveyors for solids) are used.

▪ **Storage:**

- Holding tanks for monomers, solvents, and intermediate polymer solutions.
- Silos for storing solid polymer pellets or powders.

15.(a) What is diffusion? Describe the Fick's law of diffusion.

- What is diffusion?

- Diffusion is the net movement of particles from a region of higher concentration to a region of lower concentration, driven by the random motion of individual particles. This movement continues until the concentration of the diffusing substance is uniform throughout the system, and equilibrium is reached.
 - It is a spontaneous, irreversible process that occurs in gases, liquids, and solids. The rate of diffusion depends on factors such as temperature, pressure, the nature of the diffusing substance, and the medium through which it diffuses.
 - Diffusion is a fundamental mechanism in various natural phenomena and industrial processes, including mass transfer operations, biological systems (e.g., oxygen transport in blood), and chemical reactions.
- Describe the Fick's law of diffusion.
- Fick's Laws of Diffusion quantify the rate of diffusion. There are two main laws:
 - **Fick's First Law of Diffusion:**
 - This law describes the steady-state diffusion, where the concentration gradient does not change with time.
 - It states that the molar flux of a component (the amount of substance passing through a unit area per unit time) is directly proportional to the negative of the concentration gradient.
 - Mathematically, for diffusion of component A in a mixture:

○
$$J_A = -D_{AB} \frac{dc_A}{dx}$$

○ Where:

- J_A is the molar flux of component A (mol/(m²·s) or kmol/(m²·s)).
- D_{AB} is the diffusion coefficient or diffusivity of component A in component B (m²/s). It represents how quickly A diffuses through B.
- $\frac{dC_A}{dx}$ is the concentration gradient of component A in the x-direction (mol/m⁴ or kmol/m⁴).
- The negative sign indicates that diffusion occurs down the concentration gradient, from higher to lower concentration.
- For gases, Fick's first law can also be expressed in terms of partial pressure gradient:
 - $J_A = -\frac{D_{AB}}{RT} \frac{dP_A}{dx}$ (for ideal gases)
- **Fick's Second Law of Diffusion:**
 - This law describes unsteady-state (or transient) diffusion, where the concentration changes with time. It is a mass balance equation that relates the change in concentration with time to the change in the concentration gradient with position.
 - It is often called the "diffusion equation."
 - Mathematically, for one-dimensional diffusion:
 - $\frac{\partial C_A}{\partial t} = D_{AB} \frac{\partial^2 C_A}{\partial x^2}$
 - Where:

- $\frac{\partial C_A}{\partial t}$ is the rate of change of concentration of A with respect to time.
- $\frac{\partial^2 C_A}{\partial x^2}$ is the second derivative of concentration with respect to position, representing the curvature of the concentration profile.
- This law is used to predict how concentration profiles change over time during diffusion processes, such as the drying of solids or the penetration of a solute into a stationary liquid.

16.(b) Discuss the plate type heat exchanger with suitable diagram.

- Please note: As per my instructions, I cannot create diagrams. However, I can describe the plate type heat exchanger and its components in detail.
- Plate Type Heat Exchanger:
 - A plate heat exchanger (PHE) is a type of heat exchanger that uses metal plates to transfer heat between two fluids. It is particularly efficient for liquid-to-liquid heat transfer due to its high heat transfer coefficients and compact design.
 - Construction:
 - **Plates:** The core of a PHE consists of a series of thin, corrugated metal plates. These plates are typically made of stainless steel, titanium, or other alloys, chosen based on the fluids' corrosivity. The corrugations are designed to enhance turbulence and increase the heat transfer surface area, thereby maximizing heat exchange efficiency.
 - **Gaskets:** Between each pair of plates, a rubber gasket is placed to create seals and direct the flow of the two fluids

into alternating channels. These gaskets prevent leakage and ensure that the fluids flow in their designated passages.

- **Frame:** The plates and gaskets are assembled together in a rigid frame. The frame consists of a fixed front plate (head), a movable rear plate (follower), a top carrying bar, a bottom guide bar, and tightening bolts.
- **Ports:** Inlet and outlet ports for both hot and cold fluids are located on the fixed front plate or sometimes on both the front and rear plates, depending on the flow arrangement.
- **Working Principle:**
 - The hot fluid enters through an inlet port and flows through alternate channels created by the corrugated plates.
 - Simultaneously, the cold fluid enters through another inlet port and flows through the remaining alternate channels, adjacent to those carrying the hot fluid.
 - The fluids flow in counter-current, co-current, or cross-flow arrangements, with counter-current being the most common and efficient for heat transfer.
 - Heat is transferred across the thin metal plates from the hot fluid to the cold fluid without direct mixing of the two fluids.
 - The corrugations on the plates induce high turbulence in the fluid flow even at low velocities, which significantly enhances the heat transfer coefficient and efficiency. This turbulent flow also helps in reducing fouling on the plate surfaces.

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- The processed hot and cold fluids then exit through their respective outlet ports.
- Advantages:
 - **High Thermal Efficiency:** The large surface area, thin plates, and induced turbulence lead to very high heat transfer coefficients.
 - **Compact Size:** They occupy significantly less space compared to shell-and-tube heat exchangers for the same heat duty.
 - **Easy Maintenance and Cleaning:** Plates can be easily disassembled, cleaned, inspected, and reassembled.
 - **Flexibility:** Capacity can be easily adjusted by adding or removing plates.
 - **Low Fouling:** High turbulence helps to reduce fouling.
 - **Lower Hold-up Volume:** Reduces the amount of fluid in the exchanger, which is beneficial for valuable or hazardous fluids.
- Disadvantages:
 - **Limited Temperature and Pressure:** Gaskets limit the maximum operating temperature and pressure compared to shell-and-tube exchangers.
 - **Cost of Gaskets:** Gaskets need periodic replacement, contributing to maintenance costs.
 - **Not Suitable for Fibrous Fluids:** Can be prone to clogging with fluids containing large particles or fibers.
- Applications:

- Widely used in HVAC (heating, ventilation, and air conditioning), food and beverage processing, dairy, pharmaceutical, chemical, and power generation industries for various heating, cooling, and heat recovery applications.

17.(c) A producer gas with the composition by volume, 27.3% CO, 5.4% CO₂, 0.6% O₂, 66.7% N₂ is burnt with 20% excess air. If the combustion is 98% complete, calculate the composition by volume of the flue gases.

- Basis: 100 moles of Producer Gas
- Producer Gas Composition:
 - CO = 27.3 mol
 - CO₂ = 5.4 mol
 - O₂ = 0.6 mol
 - N₂ = 66.7 mol
 - Total = 100.0 mol
- Combustion Reaction for CO: $\text{CO} + 0.5\text{O}_2 \rightarrow \text{CO}_2$
- Oxygen required for complete combustion of CO:
 - For 27.3 mol CO, required O₂ = $27.3 * 0.5 = 13.65$ mol
- Oxygen available in producer gas = 0.6 mol
- Net oxygen to be supplied from air = $13.65 - 0.6 = 13.05$ mol O₂
- Air requirement (theoretical):
 - Air consists of 21% O₂ and 79% N₂.
 - Theoretical air = $13.05 \text{ mol O}_2 * (100 \text{ mol air} / 21 \text{ mol O}_2) = 62.14$ mol air
 - Theoretical N₂ from air = $62.14 \text{ mol air} * 0.79 = 49.09$ mol N₂

- Actual air supplied: 20% excess air
 - Actual air supplied = $1.20 \times 62.14 \text{ mol} = 74.57 \text{ mol air}$
 - Actual O_2 supplied = $1.20 \times 13.05 \text{ mol} = 15.66 \text{ mol O}_2$
 - Actual N_2 supplied = $1.20 \times 49.09 \text{ mol} = 58.91 \text{ mol N}_2$
- Combustion is 98% complete for CO:
 - CO reacted = $0.98 \times 27.3 \text{ mol} = 26.754 \text{ mol CO}$
 - CO unreacted = $27.3 - 26.754 = 0.546 \text{ mol CO}$
- Products of combustion (flue gas composition):
 - **CO₂ formed from CO combustion:** 26.754 mol (since 1 mol CO produces 1 mol CO₂)
 - **Initial CO₂ in producer gas:** 5.4 mol
 - **Total CO₂ in flue gas** = $26.754 + 5.4 = 32.154 \text{ mol}$
 - **O₂ consumed:**
 - O₂ consumed for CO combustion = $0.5 \times 26.754 = 13.377 \text{ mol O}_2$
 - Total O₂ supplied (from producer gas + air) = $0.6 + 15.66 = 16.26 \text{ mol O}_2$
 - **Excess O₂ in flue gas** = Total O₂ supplied - O₂ consumed = $16.26 - 13.377 = 2.883 \text{ mol O}_2$
 - **N₂ in flue gas:**
 - N₂ from producer gas = 66.7 mol
 - N₂ from supplied air = 58.91 mol
 - **Total N₂ in flue gas** = $66.7 + 58.91 = 125.61 \text{ mol}$
 - **Unreacted CO in flue gas** = 0.546 mol CO

- Total moles of flue gas = $\text{CO}_2 + \text{Excess O}_2 + \text{N}_2 + \text{Unreacted CO}$
 - Total moles = $32.154 + 2.883 + 125.61 + 0.546 = 161.193 \text{ mol}$
- Composition by volume of flue gases (mole %):
 - $\text{CO}_2 \% = (32.154 / 161.193) * 100 = 19.95\%$
 - $\text{O}_2 \% = (2.883 / 161.193) * 100 = 1.79\%$
 - $\text{N}_2 \% = (125.61 / 161.193) * 100 = 77.92\%$
 - $\text{CO \%} = (0.546 / 161.193) * 100 = 0.34\%$
- Final Composition by Volume:
 - CO_2 : 19.95%
 - O_2 : 1.79%
 - N_2 : 77.92%
 - CO : 0.34%
 - (Sum = 100.00%)

18.(a) What are condensers and vaporizers? Discuss two-pass floating-head condenser in detail.

- What are condensers and vaporizers?
 - **Condensers:** Condensers are heat exchangers designed to condense a gaseous substance (vapor) into its liquid state by removing latent heat. This process typically occurs at a constant temperature (the saturation temperature corresponding to the operating pressure). They usually transfer heat from the hot vapor to a cooler fluid (e.g., cooling water, air). Condensers are crucial in power plants (condensing steam), refrigeration cycles (condensing refrigerant), chemical processes (condensing product vapors), and distillation columns (condensing overhead vapor).

- **Vaporizers:** Vaporizers (or reboilers, evaporators in some contexts) are heat exchangers designed to vaporize a liquid substance by adding latent heat. This process typically occurs at a constant temperature (the saturation temperature corresponding to the operating pressure). They usually transfer heat from a hot fluid (e.g., steam, hot oil) to the cooler liquid. Vaporizers are used to generate steam, reboil liquids in distillation columns, or vaporize cryogenic liquids.
- Discuss two-pass floating-head condenser in detail.
 - Please note: As per my instructions, I cannot create diagrams. However, I can describe the two-pass floating-head condenser in detail.
 - A two-pass floating-head condenser is a type of shell-and-tube heat exchanger commonly used when large temperature differences exist between the shell and tube fluids, or when cleaning of the tube side is frequently required.
 - Construction and Components:
 - **Shell:** A cylindrical vessel that encloses the tube bundle. The vapor to be condensed usually flows through the shell side.
 - **Tube Bundle:** Consists of numerous tubes running parallel to each other. The cooling fluid (e.g., water) typically flows through the inside of these tubes.
 - **Tube Sheets:** There are two tube sheets.
 - **Fixed Tube Sheet:** One tube sheet is fixed rigidly to the shell, and the tubes are expanded or welded into it.
 - **Floating Head Tube Sheet:** The other tube sheet is free to move (float) relative to the shell. This "floating head" design allows for thermal

expansion and contraction of the tubes independent of the shell, preventing thermal stresses from building up and causing damage. This is a key advantage for large temperature differentials.

- **Baffles:** Support the tubes, prevent vibration, and direct the flow of the shell-side fluid across the tube bundle to enhance heat transfer and ensure good distribution of the vapor.
 - **Pass Partitions (in Heads):** In the fixed and floating heads (bonnets), there are partitions that divide the flow path of the tube-side fluid, creating multiple passes. In a "two-pass" design, the tube-side fluid enters through an inlet nozzle, flows through half of the tubes in one direction, turns around in the floating head, and flows through the other half of the tubes in the opposite direction before exiting through the outlet nozzle. This increases the tube-side velocity, enhancing heat transfer.
 - **Vapor Inlet and Outlet Nozzles:** For the shell-side fluid (vapor and condensate). The vapor inlet is usually at the top or side of the shell, and the condensate outlet is at the bottom.
 - **Cooling Fluid Inlet and Outlet Nozzles:** For the tube-side fluid.
- Working Principle (as a Condenser):
 - The hot vapor enters the shell side, typically at the top, and flows across the tube bundle.
 - The colder cooling fluid enters the tube side through the inlet nozzle in the fixed head. It flows through the first pass of tubes, turns around in the floating head, and flows back through the second pass of tubes before exiting.

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- As the hot vapor flows over the cold tubes, it loses heat to the cooling fluid, causing it to condense into liquid.
 - The condensate collects at the bottom of the shell and is drained through the condensate outlet.
 - The two-pass arrangement on the tube side ensures a longer flow path and higher velocity for the cooling fluid, leading to improved heat transfer efficiency.
- Advantages:
 - **Accommodates Thermal Expansion:** The floating head design eliminates thermal stress issues between the shell and tubes, making it suitable for applications with large temperature differences.
 - **Tube Side Cleanability:** The floating head can be fully removed, allowing for complete access to the inside of the tubes for mechanical cleaning, which is a major advantage for fouling fluids on the tube side.
 - **Robust Design:** Generally more robust for high-pressure applications compared to gasketed plate heat exchangers.
 - Disadvantages:
 - **Higher Cost:** More complex to manufacture than fixed-tube sheet or U-tube designs.
 - **Gasket Leaks:** Has an internal gasket on the floating head, which can be a potential leak point for the shell-side fluid into the tube-side fluid.
 - **Tube Side Cleaning Only:** While the tube side is easy to clean, cleaning the shell side is more difficult due to the tube bundle's presence.
 - Applications:

- Widely used in petroleum refineries, chemical plants, and power generation for various condensation duties, especially where tube-side fouling is a concern or where significant thermal expansion compensation is needed.

19.(b) Discuss the penetration theory in details.

- The Penetration Theory (also known as the Unsteady-State Diffusion Theory or Surface Renewal Theory) is a model that describes mass transfer at a fluid-fluid interface, particularly for short contact times or rapidly changing interfaces. It was primarily developed by Higbie (1935) and Danckwerts (1951).
- Key Postulates and Details:
 - **Higbie's Penetration Theory:**
 - Higbie proposed that fluid elements (eddies or packets) from the bulk of the phase move to the interface, remain there for a short, constant period of time (contact time, t_e), and then are replaced by fresh fluid elements from the bulk.
 - During the short contact time at the interface, mass transfer occurs into the fluid element primarily by unsteady-state molecular diffusion. Convection is assumed to be negligible within the fluid element during this brief exposure.
 - The concentration profile within the fluid element is considered to be transient, similar to diffusion into a semi-infinite medium.
 - After the contact time t_e , the fluid element is completely mixed back into the bulk, and its accumulated solute is instantaneously dispersed.

- The average mass transfer coefficient (k_L) derived from Higbie's theory is proportional to $(D_{AB}/t_e)^{0.5}$, where D_{AB} is the diffusivity and t_e is the contact time. This implies that mass transfer is more efficient for higher diffusivities and shorter contact times.

▪ **Danckwerts' Surface Renewal Theory:**

- Danckwerts extended Higbie's theory by proposing that individual fluid elements at the interface are replaced by fresh fluid elements from the bulk, but the time of exposure of these elements to the interface is not constant. Instead, it follows a statistical distribution.
- He assumed that the probability of any element at the surface being replaced by a fresh element from the bulk is constant and independent of how long it has been at the surface. This "rate of surface renewal" is denoted by 's'.
- Similar to Higbie's theory, mass transfer within the fluid element at the interface occurs by unsteady-state molecular diffusion during its residence time.
- The average mass transfer coefficient (k_L) derived from Danckwerts' theory is proportional to $(D_{AB} \cdot s)^{0.5}$.
- This theory better accounts for the random nature of turbulent eddies at the interface.

○ Comparison with Two-Film Theory:

- **Two-Film Theory:** Assumes stagnant films at the interface and steady-state diffusion within these films. It is simpler and often suitable for situations where the resistance to mass transfer is predominantly in the films, and bulk fluid motion is not strongly affecting the interfacial region.

- **Penetration Theory:** Assumes unsteady-state diffusion into "fresh" fluid elements at the interface. It is generally considered more realistic for highly turbulent systems where the interface is constantly being renewed by eddies from the bulk.
- Significance and Applications:
 - The penetration theory provides a more sophisticated understanding of mass transfer in turbulent flow regimes, particularly at gas-liquid interfaces.
 - It explains why mass transfer coefficients are often observed to be higher in turbulent systems.
 - It is used in the design and analysis of mass transfer equipment such as packed columns, tray columns, and agitated vessels, where interfacial renewal plays a significant role.
 - It helps in correlating experimental mass transfer data and in predicting the performance of industrial contactors.

20.(c) What is crusher? Discuss smooth roll crusher in details.

- What is a crusher?
 - A crusher is a machine used to reduce the size of large solid materials (e.g., rocks, ores, aggregates) into smaller pieces.
 - Crushers are typically employed as primary, secondary, or tertiary stages in a comminution circuit, depending on the desired reduction ratio and product size.
 - The main mechanisms of size reduction in crushers include compression, impact, attrition (rubbing), and shear. They are extensively used in mining, quarrying, construction, and recycling industries.
- Discuss smooth roll crusher in details.

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- Smooth roll crushers (also known as smooth double roll crushers or plain roll crushers) are a type of crushing machine that primarily uses compression and some shear to reduce the size of materials. They are generally used for secondary or tertiary crushing, producing a relatively fine product with a narrow size distribution.
- Construction:
 - **Rolls:** The main components are two cylindrical rolls mounted horizontally. In a smooth roll crusher, the surfaces of these rolls are smooth, unlike toothed or corrugated rolls. These rolls are typically made of wear-resistant materials like manganese steel.
 - **Shafts and Bearings:** Each roll is mounted on a separate shaft, supported by heavy-duty bearings.
 - **Frame:** A robust frame holds the entire assembly and provides support for the rolls and driving mechanism.
 - **Drive Mechanism:** The rolls are driven by motors, often through V-belts and pulleys, or direct drives. They can rotate at the same or slightly different speeds, and usually rotate inward towards each other.
 - **Gap Adjustment Mechanism:** One roll is typically fixed, while the other is movable. A spring-loaded or hydraulic mechanism allows for adjusting the gap between the rolls. This gap (or setting) directly determines the maximum size of the crushed product. Springs also serve as a safety mechanism, allowing the rolls to spread if an uncrushable object enters, protecting the crusher from damage.
- Working Principle:

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- Material (feed) is introduced from the top, falling into the nip (the narrowest opening) between the two rotating rolls.
 - As the rolls rotate inwards, they grip the material and draw it into the crushing zone by friction.
 - The material is then subjected to intense compressive forces as it passes through the narrowing gap between the rolls.
 - The material is crushed and then discharged from the bottom of the crusher.
 - The size of the product is primarily determined by the gap setting between the rolls.
 - Smooth rolls are effective for friable, brittle, and softer materials, where a finer, more uniform product size is desired. The smooth surface minimizes tearing and produces a product with fewer fines than impact crushers.
- Advantages:
- **Fine Product:** Capable of producing a relatively fine product with a narrow size distribution.
 - **Low Fines Generation:** Less over-grinding compared to impact crushers, resulting in fewer undesirable fine particles.
 - **Low Power Consumption:** Generally energy-efficient for the crushing action.
 - **Simple Construction and Operation:** Relatively straightforward design and easy to operate.
 - **Adjustable Product Size:** The gap between the rolls can be easily adjusted to control the output size.

- **Handles Sticky Materials:** Can handle materials that might clog other crusher types, though sticky materials can still pose challenges.
- Disadvantages:
 - **Limited Reduction Ratio:** Not suitable for large primary crushing; typically used for secondary or tertiary crushing with smaller feed sizes.
 - **Wear:** Rolls are subject to wear, particularly at the feeding points.
 - **Sensitive to Hard/Abrasive Materials:** Not ideal for extremely hard or highly abrasive materials, which can cause excessive wear.
 - **Cannot Handle Tramp Metal:** Springs provide some protection, but large uncrushable objects can still cause damage.
- Applications:
 - Used in crushing coal, soft to medium-hard minerals, limestone, clay, fertilizers, and some food products. They are often employed in circuits where fine crushing is required before grinding.

21.(a) What is filtration? Discuss factors which affect rate of filtration.

- What is filtration?
 - Filtration is a mechanical or physical unit operation that separates solid particles from a fluid (liquid or gas) by passing the fluid through a porous medium (filter medium) that retains the solids.

- The fluid that passes through the filter medium is called the filtrate (or permeate), and the accumulated solids on the filter medium form a filter cake (or retentate).
 - Filtration is a crucial separation technique in various industries, including chemical, pharmaceutical, food and beverage, environmental engineering, and mining, for purposes such as product purification, clarification, dewatering, and waste treatment.
 - The driving force for filtration is a pressure difference across the filter medium.
- Discuss factors which affect rate of filtration.
- The rate of filtration (dV/dt , volume of filtrate per unit time) is influenced by several factors, which can be understood through Darcy's Law or the general filtration equation:

$$\bullet \quad \frac{dV}{dt} = \frac{A \cdot \Delta P}{\mu \cdot \left(\frac{\alpha W}{A} + R_m \right)}$$

- Where:
 - A = Filter area
 - ΔP = Pressure drop across the filter medium and cake
 - μ = Viscosity of the filtrate
 - α = Specific cake resistance
 - W = Mass of solids in the cake
 - R_m = Resistance of the filter medium
- Key factors affecting the rate of filtration:
 - **1. Pressure Drop (ΔP):**

- Directly proportional to the filtration rate. A higher pressure difference across the filter medium (e.g., using a pump or vacuum) will increase the driving force and thus the filtration rate.
- However, excessive pressure can compact the cake, increasing its resistance and sometimes leading to a decrease in rate or damage to the filter.
- **2. Filter Area (A):**
 - Directly proportional to the filtration rate. A larger filter area provides more surface for the fluid to pass through, leading to a higher filtration rate for a given pressure drop. This is why industrial filters often have large surface areas, sometimes achieved by using pleated media or multiple filter elements.
- **3. Viscosity of the Filtrate (μ):**
 - Inversely proportional to the filtration rate. Fluids with higher viscosity offer greater resistance to flow through the porous filter medium and cake, thus decreasing the filtration rate.
 - Increasing the temperature of the slurry (if it reduces viscosity) can sometimes improve filtration rates.
- **4. Specific Cake Resistance (α):**
 - Inversely proportional to the filtration rate. This property depends on the characteristics of the solid particles forming the cake (e.g., size, shape, compressibility, packing density).
 - Finer particles, irregular shapes, and compressible cakes generally lead to higher specific cake resistance, reducing the filtration rate.

- Pre-treatment of slurry (e.g., flocculation to form larger, more open aggregates) or adding filter aids (e.g., diatomaceous earth) can decrease cake resistance and improve filtration.

- **5. Concentration of Solids in Slurry:**

- A higher concentration of solids in the feed slurry will lead to a faster buildup of the filter cake. While this might seem to increase the "rate" in terms of solids collected, it also increases the cake resistance more rapidly, potentially leading to a faster decrease in the overall filtration rate over time.
- For constant-pressure filtration, a higher solids concentration results in a shorter filtration cycle time to reach a given cake thickness.

- **6. Resistance of Filter Medium (R_m):**

- Inversely proportional to the filtration rate. This resistance is due to the filter cloth, screen, or membrane itself. It depends on the pore size, thickness, and material of the filter medium.
- A tighter, finer filter medium will have higher resistance but provide better clarity of the filtrate.

- **7. Particle Size Distribution:**

- Larger, more uniform particles tend to form a more porous and less resistant filter cake, leading to higher filtration rates. Finer particles or a wide distribution of particle sizes (which allows smaller particles to fill voids between larger ones) can result in a denser, more resistant cake and lower filtration rates.

- **8. Temperature:**

- Temperature affects both the viscosity of the filtrate and sometimes the specific cake resistance (e.g., if it influences particle aggregation).
Generally, increasing temperature reduces filtrate viscosity, which increases the filtration rate.

22.(b) Explain Langmuir theory of adsorption.

- The Langmuir adsorption theory, developed by Irving Langmuir in 1916, is one of the earliest and most widely used models to describe gas-solid and liquid-solid adsorption. It is based on several key assumptions about the adsorption process:
- **Assumptions of Langmuir Adsorption Theory:**
 - **1. Monolayer Adsorption:** Adsorption occurs only at specific, localized sites on the adsorbent surface, and each site can only adsorb one molecule (adsorbate). This means that adsorption cannot proceed beyond a single layer (monolayer) of adsorbate molecules.
 - **2. Homogeneous Surface:** All adsorption sites on the surface are identical and equivalent, meaning they have the same affinity for the adsorbate.
 - **3. No Interaction Between Adsorbed Molecules:** There is no interaction (attraction or repulsion) between adsorbed molecules on adjacent sites. Once a molecule is adsorbed, it does not influence the adsorption of other molecules on neighboring sites.
 - **4. Dynamic Equilibrium:** Adsorption is a dynamic process where a state of equilibrium is reached when the rate of adsorption (molecules attaching to the surface) becomes equal to the rate of desorption (molecules detaching from the surface).
- **Derivation of the Langmuir Isotherm Equation:**

- Let θ be the fraction of the total adsorption sites that are occupied by adsorbate molecules at equilibrium.
- Then $(1 - \theta)$ is the fraction of vacant sites.
- For gas adsorption, let P be the partial pressure of the gas.
- Rate of adsorption (R_{ads}): This is proportional to the partial pressure of the gas (P) and the fraction of vacant sites $(1 - \theta)$.
 - $R_{ads} = k_a \cdot P \cdot (1 - \theta)$
 - Where k_a is the adsorption rate constant.
- Rate of desorption (R_{des}): This is proportional to the fraction of occupied sites (θ).
 - $R_{des} = k_d \cdot \theta$
 - Where k_d is the desorption rate constant.
- At equilibrium, $R_{ads} = R_{des}$:
 - $k_a \cdot P \cdot (1 - \theta) = k_d \cdot \theta$
 - Divide by k_d : $\frac{k_a}{k_d} \cdot P \cdot (1 - \theta) = \theta$
 - Let $K = \frac{k_a}{k_d}$ (Langmuir adsorption constant or equilibrium constant).
 - $K \cdot P \cdot (1 - \theta) = \theta$
 - $K \cdot P - K \cdot P \cdot \theta = \theta$
 - $K \cdot P = \theta + K \cdot P \cdot \theta$
 - $K \cdot P = \theta(1 + K \cdot P)$
 - $\theta = \frac{K \cdot P}{1 + K \cdot P}$

- Since the amount adsorbed (q_e) is proportional to the fraction of occupied sites (θ), we can write:

- $q_e = q_m \cdot \theta$

- Where q_m is the maximum adsorption capacity (amount adsorbed when the surface is completely covered by a monolayer).

- Substituting θ :

- $q_e = \frac{q_m \cdot K \cdot P}{1 + K \cdot P}$ (for gas adsorption)

- For liquid adsorption, P is replaced by equilibrium concentration C_e :

- $q_e = \frac{q_m \cdot K \cdot C_e}{1 + K \cdot C_e}$ (for liquid adsorption)

- **Significance and Limitations:**

- The Langmuir isotherm accurately describes adsorption for many systems, especially at low to moderate concentrations, and when a single layer of adsorption occurs.
- The constant q_m provides an estimate of the maximum adsorption capacity, and K relates to the affinity between the adsorbate and adsorbent.

- **Limitations:**

- The assumption of a homogeneous surface is often not true in reality, as surfaces can be heterogeneous.
- It does not account for multilayer adsorption, which occurs at higher pressures, especially with porous adsorbents.

- It neglects interactions between adsorbed molecules, which can be significant, especially at higher surface coverage.
- Therefore, it may not provide a good fit for all adsorption systems, particularly those involving multilayer adsorption (like BET isotherm is used for) or heterogeneous surfaces (like Freundlich isotherm is used for).

23.(c) Discuss the double-pipe heat exchangers.

- Please note: As per my instructions, I cannot create diagrams. However, I can describe the double-pipe heat exchangers in detail.
- Double-Pipe Heat Exchangers:
 - A double-pipe heat exchanger is the simplest type of heat exchanger, consisting of two concentric pipes (one pipe inside another larger pipe). The fluids flow in the annular space between the inner and outer pipes, and through the inner pipe.
 - Construction:
 - **Inner Pipe:** This is typically a standard pipe through which one fluid flows.
 - **Outer Pipe (Shell):** This is a larger pipe that encloses the inner pipe, creating an annular space. The second fluid flows through this annulus.
 - **Return Bends (Hairpin Sections):** To achieve longer heat transfer lengths in a compact arrangement, multiple double-pipe sections are connected in series using U-bends (hairpin bends). This allows the fluid to flow back and forth.

- **Headers/Connections:** Inlet and outlet nozzles for both fluids are provided at the ends of the double-pipe sections.
- **Sealing:** Appropriate sealing mechanisms (e.g., flanges, packed glands) are used at the ends to prevent leakage between the two fluid streams and to the atmosphere.
- **Working Principle:**
 - One fluid flows through the inner pipe, and the other fluid flows in the annular space between the inner and outer pipes.
 - Heat is transferred across the wall of the inner pipe from the hotter fluid to the colder fluid.
 - The flow arrangement can be co-current (both fluids flow in the same direction) or, more commonly, counter-current (fluids flow in opposite directions) for higher thermal efficiency.
 - The length of the double-pipe unit can be increased by connecting multiple hairpin sections in series, allowing for significant heat transfer even with a relatively simple design.
- **Advantages:**
 - **Simplicity:** Very simple in design and construction.
 - **Cost-Effective (for Small Duties):** Economical for small heat transfer duties or when only a small number of heat transfer units are required.
 - **High Pressure Capability:** Can handle high operating pressures effectively.

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- **Easy to Clean:** Relatively easy to clean, especially the inner pipe. The outer pipe can also be cleaned if access is designed.
 - **Flexible:** Capacity can be adjusted by adding or removing hairpin sections.
 - **Good for High Viscosity Fluids:** Can handle viscous fluids efficiently due to relatively large flow passages.
 - **Counter-Current Flow:** Easily achieves true counter-current flow, which is the most efficient flow arrangement for heat transfer.
- Disadvantages:
- **Low Heat Transfer Area per Unit Volume:** Relatively small heat transfer surface area compared to their overall footprint, making them less suitable for large heat transfer duties. They require a large space for large capacities.
 - **High Space Requirement:** Occupy a significant amount of space for larger duties.
 - **Cannot Handle Large Flow Rates:** Limited by the capacity of the pipes, not suitable for very high flow rates.
 - **Higher Pressure Drop:** The long, narrow flow paths can lead to higher pressure drops.
- Applications:
- Commonly used for small-scale heat transfer duties in laboratories or pilot plants.

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- Suitable for processes involving highly corrosive fluids (where special alloys are needed for only one pipe), high pressures, or highly viscous fluids.
- Used for heating or cooling individual process streams, such as in solvent heating/cooling, oil heating, and small-scale chemical processing.

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