Ministry of high Education and Scientific Research
Southern Technical University
Technological institute of Basra
Department of Chemical Industries Techniques

Learning package

Operation industrial units

For

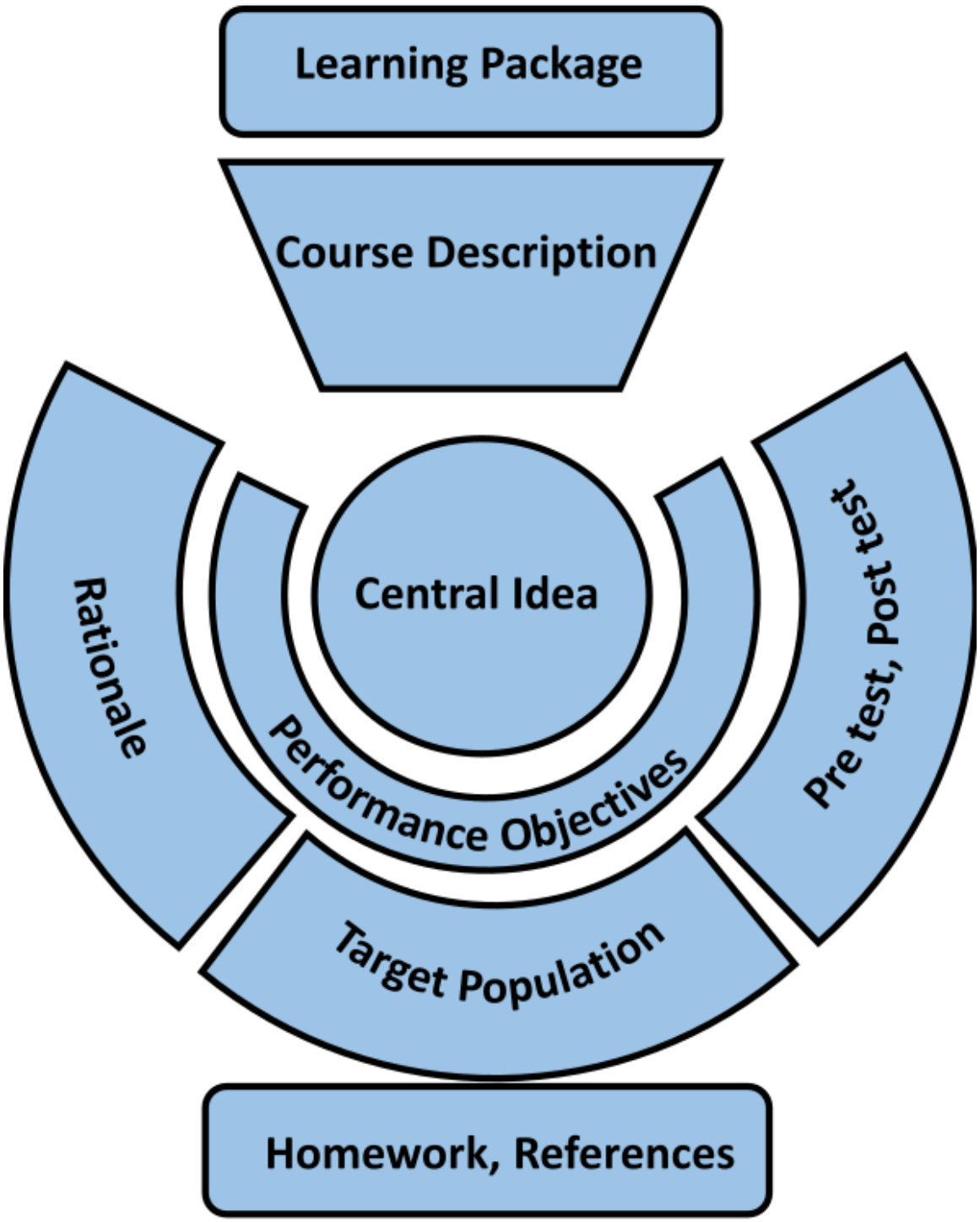
First year students

By

Halah Kadhim Mohsin

Dep. Of Chemical industries Techniques

2025


Learning Package
Course Description
Rationale
Central Idea
Performance Objectives
Pre test, Post test
Target Population
Homework, References

Course Description

Course Name:	
Operation industrial units	
Course Code:	
Semester / Year:	
Semester	
Description Preparation Date:	
25/ 06/ 2025	
Available Attendance Forms:	
Attendance only	
Number of Credit Hours (Total) / Number of Units (Total)	
60 hours/4 hour weekly/ unit	
Course administrator's name (mention all, if more than one name)	
Name: Halah Kadhim Mohsin Email: hala.alkhafaji@stu.edu.iq	
Course Objectives	
1. Understand Solid-Fluid Dynamics & Separation: Comprehend the principles of fluidization, sedimentation, and thickening, and their applications in industrial processes. 2. Analyze Mechanical Separation Techniques: Identify and explain various mechanical separation methods, including screen analysis, centrifugation, cyclonic separation, and flotation, along with their associated equipment. 3. Master Filtration Processes: Describe the fundamental principles of filtration and differentiate between various types of filtration equipment and their operational characteristics. 4. Operate Size Reduction & Mixing Equipment: Understand the mechanisms of size reduction and mixing for solids and	

pastes, including the operation, energy consumption, heat removal, and equipment types involved. 5. Apply Materials Logistics & Storage Principles: Acquire knowledge of effective materials handling techniques and principles of industrial storage, including different storage systems and their applications. 6. Prioritize Operational Efficiency & Safety: Recognize and apply fundamental considerations for efficient and safe operation across all discussed unit operations, including troubleshooting basics.	
Teaching and Learning Strategies	
1. Interactive Lectures: Engaging theoretical delivery with Q&A and discussions. 2. Problem-Solving Exercises: Regular practice applying concepts to solve problems. 3. Case Study Analysis: Examining real-world industrial scenarios. 4. Multimedia Learning: Utilizing videos, animations, and virtual tours. 5. Hands-on/Simulation: Practical experience through labs or software. 6. Collaborative Learning: Group work and peer-to-peer instruction. 7. Formative Assessments: Continuous monitoring of understanding with feedback. 8. Industry Connection: Guest speakers and discussions on current trends.	

Course Structure

Weeks	Hours	Required Learning Outcomes	Unit or subject name	Learning method	Evaluation method
1	4hours	Identify fluidization types, conditions, and applications.	Fluidization	Lecture + written summary	Weekly Quizzes
2	4hours	Classify mechanical separation methods and select suitable ones.	Mechanical separation	Lecture + comparison table	Homework Assignments
3	4hours	Perform sieve analysis and calculate particle size distribution.	Screen analysis	Sample problems + calculations	Quizzes on pressure concepts
4	4hours	Explain settling behavior and design thickening units.	Sedimentation and thickening	Theory explanation + exercises	Monthly Exam 1
5	4hours	Understand centrifuge principles and choose appropriate types.	Centrifuge	Text reading + short answer questions	Problem Set Submission
6	4hours	Explain gas-solid separation and evaluate cyclone efficiency.	Cyclone	Diagram analysis + problem solving	Weekly Quizzes
7	4hours	Describe flotation mechanism and	Flotation	Definitions + group discussion	Homework Assignment

		influencing factors.			
8	4hours	Understand filtration types and apply basic equations.	Filtration	Lecture + numerical problems	Monthly Exam 2
9	4hours	Identify filtration equipment and match to process needs.	Filtration equipment	Table completion + description task	Quizzes on friction factor determination
10	4hours	Explain size reduction mechanisms and calculate energy needs.	Size reduction	Theory + example solving	Problem Set Submission
11	4hours	Compare equipment types and select appropriate one.	Size reduction equipment	Matching terms with functions	Homework Assignment / Project Part 1
12	4hours	Control feed, manage energy use, and handle heat removal.	Size reduction equipment operation (Feed control, energy consumption , removal of heat)	Case questions + theoretical analysis	Weekly Quizzes
13	4hours	Explain mixing methods and evaluate homogeneity.	Mixing of solids and pastes	Definitions + discussion	Final Project Part 2 / Presentation (if applicable)
14	4hours	Identify handling equipment and design efficient systems.	Materials handling	Classification tasks + written notes	Final Exam (Covers all course material)

Distribution as follows: 20 points for Midterm Theoretical Exams for the first semester, 20 points for Midterm Practical Exams for the first semester, 10 points for Daily Exams and Continuous Assessment, and 50 points for the Final Exam.	
Learning and Teaching Resources	
Ref.	1) Unit operation of chemical Eng. By Maccabe , 4th edition 1993 . 2) Chemical Engineering Fluid Mechanics, 2 th edition Ron Derby, Marcel Dekker Ind. , 2001 3) Mechanics of Solids William B. Bickford of Applications Homewood, Boston, 1993. 4) Fluid flow for Chemical Engineers, By F. A. Holland 2nd edition , 1995 5) Solution of problems in fluidMechanics , part 1 by JF Douglas, 1974 . 6) Chemical Eng. Vol. (1) and (2) by Coulson Richardson , 2001 . 7) Perry's Chemical Engineers Hand book James O. Maloney , 8th ed. , 2008 .

Ministry of high Education and Scientific Research
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Department of Chemical Industries Techniques

Learning package

In

Fluidization

For

Students of First Year

By

Halah Kadhim Mohsin

Dep. Of Chemical industries Techniques

2025

1/ Overview

1/ A – Target Population: Technical institute students specializing in chemical technology or similar industrial fields

1 / B – Rationale

- **Key Industrial Technology:** Widely used for excellent mixing, high heat/mass transfer, and handling fine solids.
- **Efficiency & Control:** Improves energy efficiency and used in environmental control (e.g., combustion, pollutant removal).
- **Process Versatility:** Enables various chemical and physical operations.

1 / C – Central Idea

- To explain how solid particles behave when an upward fluid flow transforms a fixed bed into a fluidized state, exploring different fluidization regimes, and their practical industrial significance.

1 / D – Performance Objectives Upon completion, students will be able to:

- **Define** fluidization and its distinct characteristics.
- **Describe** the onset of fluidization (Umf) and key fluidization regimes.
- **Calculate** minimum fluidization velocity.
- **List** advantages/disadvantages and **identify** industrial applications of fluidized beds.

2 / Pre-test

- Difference between fixed and fluidized beds?
- Effect of increasing fluid velocity on pressure drop?
- Example of industrial solid-fluid contact?
- What is minimum fluidization velocity?

3/ Lecture

1. Introduction to Fluidization

Definition: Fluidization is a process whereby a granular material (typically solid particles) is transformed into a fluid-like state by passing a fluid (gas or liquid) upwards through the particle bed at a sufficient velocity. When this critical velocity is reached, the particles become suspended in the fluid, the bed expands, and the mixture behaves like a boiling liquid, exhibiting properties such as excellent mixing, uniform temperature, and ease of transport.

Importance in Chemical Engineering: Fluidization is a cornerstone operation in chemical engineering, primarily exploited for:

- **Enhanced Heat and Mass Transfer:** The intense mixing and large surface area of suspended particles lead to very high rates of heat and mass transfer between the fluid and solid phases. This is crucial for efficient chemical reactions and thermal processes.
- **Catalytic Reactions:** Fluidized bed reactors (FBRs) are ideal for heterogeneous catalytic reactions due to their excellent temperature control (minimizing hot spots), high contact efficiency between reactants and catalyst, and ease of catalyst regeneration.
- **Drying and Coating:** Uniform temperature and good contact make them suitable for drying powders and granulating/coating particles.

- **Controlled Solid Handling:** Fluidized beds allow solids to be transported and handled like fluids, simplifying complex processing lines.

2. Principles of Fluidization

Consider a bed of solid particles resting on a distributor plate through which fluid (gas or liquid) is introduced from below.

1. **Fixed Bed:** At very low fluid velocities, the fluid simply flows through the voids between the stationary particles. The pressure drop across the bed increases linearly with velocity.
2. **Minimum Fluidization Velocity (umf):** As the fluid velocity increases, the drag force on the particles increases. At a certain critical velocity, the drag force on the particles plus the pressure force equals the gravitational force on the particles. At this point, the bed begins to expand, and the particles become suspended. This is the **minimum fluidization velocity**.
    - **Chemical Engineering Significance:** Calculating umf is essential for designing fluidized beds, as it determines the minimum fluid flow rate required to achieve fluidization.
    - **Equation (Ergun Equation for pressure drop, then setting ΔP=weight of bed):** For laminar flow through packed beds:

$$\frac{\Delta P}{L} = \frac{150\mu u(1-\epsilon)^2}{D_p^2\epsilon^3}$$

For turbulent flow:

$$\frac{\Delta P}{L} = \frac{1.75\rho_f u^2(1-\epsilon)}{D_p\epsilon^3}$$

At minimum fluidization, the pressure drop equals the weight of the bed per unit area:

$$\frac{\Delta P}{L} = (\rho_s - \rho_f)g(1-\epsilon_{mf})$$

Equating these for ΔP_{mf} gives the u_{mf} (often a more complex, empirical approach like the Wen and Yu correlation is used for practical applications, considering both laminar and turbulent regimes):

$$Re_{mf} = \frac{D_p u_{mf}\rho_f}{\mu}$$

$$Re_{mf} = \sqrt{(33.7)^2 + 0.0408Ar} - 33.7$$

(for $Ar < 10^5$) Where Ar (Archimedes number) is a dimensionless group representing the ratio of gravitational to viscous forces: $Ar = \frac{D_p^3\rho_f(\rho_s-\rho_f)g}{\mu^2}$ This highlights the role of particle size (D_p), fluid density (ρ_f) and viscosity (μ), and solid density (ρ_s) in determining fluidization conditions.

3. **Expanded Bed (Particulate Fluidization):** Slightly above u_{mf}, the bed expands uniformly. This is common with liquid fluidization.
4. **Bubbling Fluidization (Aggregative Fluidization):** For gas-solid systems, as velocity increases further, the excess gas tends to form bubbles that rise through the bed, similar to bubbles in a boiling liquid. This is the most common regime for gas-solid fluidized beds.
5. **Turbulent Fluidization:** At even higher velocities, bubbles become unstable, and the gas-solid mixture becomes highly turbulent.
6. **Fast Fluidization & Transport/Circulating Fluidization:** At very high velocities, most particles are entrained and carried out of the bed, requiring an external cyclone to separate and return them to the bed (Circulating Fluidized Bed - CFB). This is crucial for continuous processes like FCC.

3. Types of Fluidized Beds

- **Bubbling Fluidized Bed (BFB):**
  - **Characteristics:** Distinct bubbles rising through a dense phase of particles.

    - **Advantages:** Excellent mixing, uniform temperature, good for exothermic reactions due to effective heat removal.
    - **Disadvantages:** Poor gas-solid contact (gas bypasses in bubbles), particle elutriation (carry-over of fine particles).
    - **Applications:** Incineration, coal combustion, calcination.
- **Circulating Fluidized Bed (CFB):**
    - **Characteristics:** Operates at much higher gas velocities than BFBs, where a significant portion of the particles are carried out of the reactor and then separated by cyclones and returned. This creates two distinct zones: a dense lower zone and a dilute upper zone (riser).
    - **Advantages:** Very high gas-solid contact efficiency, high throughput, excellent for reactions requiring continuous catalyst regeneration.
    - **Disadvantages:** Higher pressure drop, more complex system (requires cyclones and standpipes).
    - **Key Application: Fluid Catalytic Cracking (FCC) in petroleum refining** – this is a prime example of CFB application where catalyst particles (solid) facilitate cracking of heavy hydrocarbons (fluid) into lighter products, with continuous regeneration of the coked catalyst.
- **Packed-Fluidized Bed:** A hybrid where a packed bed is designed to fluidize, offering benefits of both.
- **Spouted Bed:** Used for coarser particles or those with a wide size distribution, where the fluid is introduced through a central nozzle creating a spout.

4. Chemical Engineering Applications of Fluidized Beds

1. **Fluid Catalytic Cracking (FCC) Reactors:** The most significant application. Catalyst particles are fluidized to

facilitate the cracking of crude oil fractions. The excellent heat transfer manages the highly exothermic regeneration of the coked catalyst.

2. **Combustion and Gasification:** Efficient burning of coal, biomass, or waste due to good mixing and temperature control, minimizing pollutants like NOx.
3. **Drying:** Uniform drying of granular products (e.g., pharmaceuticals, food products, polymers) due to excellent heat and mass transfer.
4. **Granulation and Coating:** Uniform coating of particles (e.g., pharmaceutical tablets, fertilizers) by spraying a liquid onto a fluidized bed.
5. **Roasting and Calcination:** Thermal treatment of ores and chemicals (e.g., limestone calcination, sulfide ore roasting) due to uniform temperature.
6. **Fischer-Tropsch Synthesis:** For converting syngas into liquid hydrocarbons, often utilizing iron-based catalysts in fluidized beds.
7. **Phthalic Anhydride Production:** Catalytic oxidation in fluidized beds.

5. Design and Operational Considerations for Chemical Engineers

- **Reactor Design:** For catalytic reactors, key parameters include bed height, diameter, distributor design, particle residence time distribution, and gas residence time.
- **Heat Transfer:** Designing for efficient heat removal (for exothermic reactions) or supply (for endothermic reactions) through internal heat exchange surfaces (e.g., coils).
- **Mass Transfer:** Ensuring good contact between reactants and catalyst/solid.
- **Particle Properties:** The size, density, shape, and distribution of the particles critically influence fluidization behavior (umf, bubbling characteristics). Understanding these properties is

vital for selecting appropriate particles (e.g., catalyst particles).

- **Fluid Properties:** Gas/liquid density and viscosity directly impact umf and pressure drop.
- **Distributor Plate Design:** Ensures uniform fluid distribution across the bed, preventing channeling and improving efficiency. Orifice size and spacing are critical.
- **Elutriation/Entrainment Control:** Designing cyclones (as we discussed) to efficiently separate and return fine particles to the bed, maintaining catalyst inventory and minimizing environmental emissions.
- **Pressure Drop:** Managing pressure drop across the bed and distributor, which affects fan/blower power requirements.
- **Safety:** Handling hot solids and reactive gases requires careful design to prevent defluidization, runaway reactions, or dust explosions.

Example Problem: Minimum Fluidization Velocity Calculation (Chemical Engineering Focus)

Problem Statement:
A pilot-scale fluidized bed reactor is being designed to process granular catalyst particles. The particles have an average diameter (D_p) of $150\ \mu\text{m}$ and a density (ρ_s) of $2500\ \text{kg/m}^3$. Air at $25^\circ C$ and $1\ \text{atm}$ (density $\rho_f = 1.18\ \text{kg/m}^3$, viscosity $\mu = 1.85 \times 10^{-5}\ \text{Pa} \cdot \text{s}$) is used as the fluidizing medium. Estimate the minimum fluidization velocity (u_{mf}) for this system, assuming the voidage at minimum fluidization (ϵ_{mf}) is 0.4.

Given Data:

- Particle diameter, $D_p = 150\ \mu\text{m} = 150 \times 10^{-6}\ \text{m}$
- Particle density, $\rho_s = 2500\ \text{kg/m}^3$
- Fluid (Air) density, $\rho_f = 1.18\ \text{kg/m}^3$
- Fluid viscosity, $\mu = 1.85 \times 10^{-5}\ \text{Pa} \cdot \text{s}$
- Voidage at minimum fluidization, $\epsilon_{mf} = 0.4$
- Gravitational acceleration, $g = 9.81\ \text{m/s}^2$

Solution Approach (Using the approximate Ergun-based equation for u_{mf}):
For practical engineering calculations, a common approach for u_{mf} is derived from the Ergun equation by equating the pressure drop at u_{mf} to the bed weight. For most cases, particularly smaller particles, the viscous term (laminar flow contribution) dominates.

A simplified form for u_{mf} (often derived from balancing pressure drop with bed weight for laminar flow):

$$u_{mf} = \frac{D_p^2 (\rho_s - \rho_f) g}{150 \mu} \frac{\epsilon_{mf}^3}{(1 - \epsilon_{mf})}$$

(Note: More accurate methods involve iterative solutions or correlations using dimensionless groups like Archimedes number, but this simplified form provides a good estimate for typical catalyst particles).

1. **Substitute the values into the equation:**

$$u_{mf} = \frac{(150 \times 10^{-6})^2 \times (2500 - 1.18) \times 9.81}{150 \times (1.85 \times 10^{-5})} \times \frac{(0.4)^3}{(1 - 0.4)}$$

2. **Calculate terms:**
   - $D_p^2 = (1.5 \times 10^{-4})^2 = 2.25 \times 10^{-8}\ \text{m}^2$

- $(\rho_s - \rho_f) = 2498.82\ \text{kg/m}^3$
- Numerator (excluding fraction): $2.25 \times 10^{-8} \times 2498.82 \times 9.81 = 5.511 \times 10^{-4}$
- Denominator: $150 \times 1.85 \times 10^{-5} = 0.002775$
- Fraction term: $\frac{(0.4)^3}{(0.6)} = \frac{0.064}{0.6} \approx 0.1067$

3. Calculate u_{mf}:

$$u_{mf} = \frac{5.511 \times 10^{-4}}{0.002775} \times 0.1067$$

$$u_{mf} \approx 0.1986 \times 0.1067$$

$$u_{mf} \approx 0.0212\ \text{m/s}$$

Answer: The estimated minimum fluidization velocity for this system is approximately $0.0212\ \text{m/s}$. This value is crucial for determining the gas flow rate needed to successfully fluidize the catalyst particles in the reactor.

4/ Post-test

- Draw pressure drop vs. velocity curve, label Umf.
- Explain bubbling bed advantages/disadvantages for reactions.
- Describe two industrial fluidization applications.
- Calculate Umf given data.
- Compare fluidized vs. fixed beds (pros/cons).

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5 / Homework

- **Chemical Engineering Rationale:**
  - Explain why fluidized beds are particularly advantageous for **exothermic catalytic reactions** in

chemical processes, focusing on their thermal characteristics.
    - In a gas-solid fluidized bed, if you increase the density of the fluidizing gas (e.g., by increasing pressure or changing gas type), how would this likely affect the minimum fluidization velocity (umf)? Justify your answer using the underlying principles.
- **Application and Design:**
    - Describe the primary differences between a Bubbling Fluidized Bed (BFB) and a Circulating Fluidized Bed (CFB) in terms of their operating velocity regimes and particle entrainment. Give a specific example of a major industrial chemical process that utilizes CFB technology and explain *why* CFB is preferred for that process.
    - A chemical engineer needs to select a catalyst for a new fluidized bed reactor. Besides catalytic activity, what key *physical properties* of the catalyst particles would be critical considerations for successful fluidization and reactor operation?
- **Advanced Concept:**
    - What is "particle attrition" in the context of fluidized beds? Why is it a significant concern for chemical engineers, especially in catalytic processes, and what measures can be taken to mitigate it?

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6 / References

- Key textbooks (Kunii & Levenspiel, Rhodes).
- Relevant journals (Powder Technology, Chem Eng Sci).

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Learning package

In

Mechanical separation

For

Students of First Year

By

Halah Kadhim Mohsin

Dep. Of Chemical industries Techniques

2025

1/ Overview

- **1/ A – Target Population:** Technical institute students specializing in chemical technology or similar industrial fields.
- **1/ B – Rationale:** To understand various methods and equipment used for separating components based on their physical properties in industrial settings.
- **1/ C – Central Idea:** The use of physical forces to divide mixtures into different parts, usually to isolate a desired product or remove impurities.
- **1/ D – Performance Objectives:**
  - By the end of this lecture, students will be able to define mechanical separation.
  - To list common types of mechanical separation.
  - To identify the basic principles behind these separation methods.

2/ Pretest

- What is the difference between mixing and separating?
- Can you separate sand from water using only your hands? Why or why not?
- What happens to heavy particles in a liquid if you leave it still for a long time?

3/ Lecturer

1. Introduction to Mechanical Separation

Definition: Mechanical separation is a physical unit operation used to separate heterogeneous mixtures into two or more distinct phases (e.g., solid from liquid, solid from gas, solid from solid, or liquid from liquid) based on differences in their physical properties, such as size, density, or shape, using mechanical means. It is distinct from chemical separation processes (like distillation, absorption, or extraction) which rely on chemical potential or phase equilibria.

Chemical Engineering Significance: Mechanical separation is a cornerstone operation in almost every chemical plant and refinery, playing a crucial role in:

- **Product Purification:** Removing undesirable solid impurities from liquid or gaseous products to meet quality specifications.
- **Recovery of Valuable Components:** Separating a valuable solid catalyst or a solid product from a fluid stream.
- **Waste Treatment:** Removing solids from liquid effluents (wastewater) or particulate matter from gas emissions to comply with environmental regulations.
- **Preparation for Downstream Processes:** Conditioning streams (e.g., dewatering slurries before drying, removing fines before a reaction).
- **Resource Efficiency:** Recycling materials, reducing losses.

Mechanical separation operations can be broadly classified by the phases being separated:

- **Solid-Fluid Separation:** Separating solids from liquids (e.g., filtration, sedimentation, centrifugation) or solids from gases (e.g., dust collection, cyclones). This is the most common application in chemical processing.
- **Solid-Solid Separation:** Separating different solid particles from each other (e.g., screening, air classification).

2. Solid-Fluid Separation

These operations are designed to separate particulate solids suspended in a liquid or gaseous continuous phase.

A. Sedimentation and Clarification (Liquid-Solid Separation by Gravity)

- **Principle:** Relies on the density difference between the solid particles and the liquid. Denser solid particles settle out of a quiescent or slowly flowing liquid under the influence of gravity.
- **Chemical Engineering Relevance:** The design of settling tanks and clarifiers involves understanding particle settling velocity (often described by **Stokes' Law** for fine particles in laminar flow, or more complex models for larger particles), retention time, and overflow rate to ensure efficient separation.
- **Equipment:**
  - **Thickeners/Clarifiers:** Large, typically circular tanks with rakes that slowly rotate to consolidate the settled solids (sludge) at the bottom and collect clarified liquid (overflow) at the top. Designed for continuous operation.
  - **Settling Basins:** Simpler, often rectangular tanks, typically used for primary settling in wastewater treatment.
- **Applications:**
  - **Wastewater treatment (primary clarification)** to remove suspended solids.
  - **Thickening slurries** (e.g., catalyst slurries, mineral slurries) to increase their solids concentration prior to filtration or centrifugation.
  - Recovering coarser **catalyst particles** from recycle streams.

B. Filtration (Liquid-Solid or Gas-Solid Separation)

- **Principle:** Separates solids from a fluid by passing the fluid through a porous medium (filter medium) that retains the solid particles while allowing the fluid (filtrate or gas) to pass through.
- **Chemical Engineering Relevance:** Key considerations include the choice of filter medium (pore size, material compatibility, pressure drop), filter cake formation (compressibility, specific cake resistance), washing efficiency, and dewatering. **Darcy's Law** is fundamental for understanding fluid flow through porous media.
- **Types of Filtration:**
  - **Surface Filtration:** Solids collect on the surface of the filter medium (e.g., screen filters, filter presses).
  - **Depth Filtration:** Solids are captured within the filter medium (e.g., sand filters, cartridge filters).
- **Equipment:**
  - **Plate-and-Frame Filter Press:** Batch operation, widely used for highly concentrated slurries and fine particles. Can achieve high pressures and produce a dry cake.
  - **Rotary Vacuum Filter:** Continuous operation, typically for large volumes of dilute slurries. A rotating drum picks up slurry, forms a cake, which is then dewatered and washed, and finally discharged.
  - **Centrifugal Filters (Centrifuges with filter medium):** Combine centrifugal force with a filter medium to achieve high dewatering rates for granular or crystalline solids.
  - **Bag Filters/Fabric Filters (Gas-Solid):** Industrial dust collectors using fabric bags or envelopes to filter particulate matter from gas streams. Highly efficient for very fine dusts.
  - **Cartridge Filters:** Disposable or reusable cartridges used for polishing (final removal of fine suspended

solids) in liquid streams, especially for sensitive products.

- **Applications:**
  - **Catalyst recovery** (e.g., after a slurry polymerization process or from a catalyst washing step).
  - **Product purification** (removing solid impurities or haze from liquid products like refined oils, specialty chemicals, or pharmaceutical solutions).
  - **Wastewater polishing** after biological treatment.
  - **Air pollution control** (dust collection from vent streams, flue gases, or pneumatic conveying systems).

C. Centrifugation (Liquid-Solid, Liquid-Liquid, or Gas-Solid Separation by Centrifugal Force)

- **Principle:** Applies a centrifugal force (many times greater than gravity) to accelerate the separation of components with different densities. The heavier phase moves radially outward, and the lighter phase moves inward.
- **Chemical Engineering Relevance:** Design factors include the "G-force" (relative centrifugal force), bowl speed, retention time, and the rheological properties of the mixture. Centrifuges are highly effective for separating fine particles or emulsions that are difficult to separate by gravity.
- **Types:**
  - **Sedimenting Centrifuges (Solid Bowl):** No filter medium. Solids settle against the bowl wall, and liquid overflows. Examples: **Decanter centrifuges** (conical bowl with a screw conveyor for continuous solid discharge) for dewatering slurries, **Disk-stack centrifuges** for clarifying liquids or separating liquid-liquid emulsions.
  - **Filtering Centrifuges (Perforated Basket):** A perforated basket lined with a filter medium. Liquid

passes through, and solids are retained. Examples: **Basket centrifuges** for dewatering crystalline products.

- **Applications:**
  - **Dewatering slurries** (e.g., catalyst slurries, polymer slurries, industrial sludges) to reduce moisture content.
  - **Clarification of liquids** (e.g., purification of lubricating oils, removal of fine solids from fuels).
  - **Separation of liquid-liquid emulsions** (e.g., oil-water mixtures).
  - Separation of fine particles in biotechnology and pharmaceutical production.

D. Cyclones (Gas-Solid or Liquid-Solid Separation by Centrifugal Force)

- **Principle:** Uses a swirling (vortex) motion to separate particles from a fluid stream based on inertial forces. The solid-laden fluid enters tangentially, creating a vortex. Heavier particles are thrown to the wall, lose momentum, and slide down to a collection hopper, while the cleaner fluid exits from the top.
- **Chemical Engineering Relevance:** Simplicity, relatively low capital and operating costs, no moving parts, but separation efficiency depends on particle size (less efficient for very fine particles) and pressure drop. Often used as a primary separation step.
- **Equipment:** Conical vessel with a tangential inlet and top/bottom outlets.
- **Applications:**
  - **Primary dust collection in various industrial processes**, particularly in **Fluid Catalytic Cracking (FCC) units**, where cyclones are **critical for separating circulating catalyst particles from the gaseous flue products** in both the reactor and regenerator.

    - Pre-cleaning of gas streams before more efficient (and expensive) filters like baghouses.
    - Removal of coarse particles from gas streams in power plants (e.g., fly ash).
    - **Hydrocyclones** (liquid-solid separation): Used for thickening slurries or separating fine solids from liquids, especially in mineral processing.

3. Solid-Solid Separation

These operations separate different solid particles from each other based on size, density, or other physical properties, typically without a continuous fluid phase.

A. Screening (Sieving)

- **Principle:** Separates particles solely based on their size using a mesh or perforated surface with precisely sized openings. Particles smaller than the openings pass through (undersize), while larger ones are retained (oversize).
- **Chemical Engineering Relevance:** Critical for controlling particle size distribution (PSD) of products, ensuring uniform feed to downstream processes, or removing undesirable large/small particles. Screen aperture size, mesh material, and vibration characteristics are key design parameters.
- **Equipment:** Vibrating screens (most common), gyratory screens, trommels (rotating cylindrical screens).
- **Applications:**
    - **Classifying different catalyst particle sizes** for specific reactor applications (e.g., FCC catalyst fines removal or particle size grading).
    - Separating **polymer pellets** into uniform sizes.
    - Removing oversized lumps or undersized fines from bulk solid products (e.g., fertilizers, specialty chemicals).
    - Quality control of powdered or granular products.

B. Elutriation (Air Classification)

- **Principle:** Separates particles based on their terminal settling velocity in a fluid (typically air). A rising fluid stream is introduced into a vertical column. Lighter/finer particles are carried upwards by the fluid, while heavier/coarser particles fall against the fluid flow and are collected at the bottom.
- **Chemical Engineering Relevance:** Precise control of fluid velocity is essential to achieve the desired cut point (the particle size at which separation occurs). Used when a very fine separation or removal of "fines" is required.
- **Equipment:** Vertical classification columns or specialized air classifiers integrated with mills.
- **Applications:**
    - Removing ultrafine particles (fines) from granular or powdered materials, particularly in **catalyst recovery and classification**, where fines can be problematic for fluidization or lead to excessive emissions.
    - Separating components with different densities.
    - Often integrated with grinding circuits (closed-circuit grinding) to recycle oversized particles.

4. Chemical Engineering Design & Operational Considerations for Mechanical Separation

1. **Material Characterization (Paramount):**
    - **Particle Size Distribution (PSD):** Crucial for all mechanical separations.
    - **Density:** Of both solid and fluid phases.
    - **Particle Shape:** Affects settling, filtration, and screening.
    - **Cohesiveness/Stickiness:** Can blind filters, cause caking in centrifuges or hoppers, or make screening difficult.

    - **Abrasiveness:** Causes wear on equipment (filters, centrifuge bowls, cyclone walls).
    - **Compressibility (for Filter Cakes):** Affects filtration rate and cake dewatering.
    - **Fluid Viscosity:** Affects settling velocity and filtration rate.
2. **Required Separation Efficiency:** Defining the target purity of the separated phases (e.g., solids content in liquid effluent in parts per million (ppm), moisture content in solid cake as a percentage).
3. **Throughput/Capacity:** The volume or mass of mixture to be processed per unit time. This determines the size and number of units.
4. **Continuous vs. Batch Operation:** Selection based on upstream/downstream process continuity, required flexibility, and economic considerations.
5. **Pressure Drop/Energy Consumption:** Especially significant for filtration (pump power) and cyclones (blower/fan power). Centrifuges also have high power consumption.
6. **Cost Analysis:** Balancing initial Capital Expenditure (CAPEX) for equipment against Operational Expenditure (OPEX) including energy, maintenance, consumables (filter media, replacement parts), and labor.
7. **Safety:**
    - Handling hazardous, flammable, or toxic materials requires enclosed systems, inerting, and proper ventilation.
    - High pressures (e.g., filter presses) or high rotational speeds (e.g., centrifuges) require robust mechanical design and safety interlocks.
    - Dust explosions (for fine, combustible powders) require specific design features (e.g., explosion venting, inert blanketing in bag filters, proper grounding).
8. **Environmental Impact:** Minimizing emissions (particulate matter from dust collectors, liquid discharge from clarifiers),

managing and disposing of separated waste streams (e.g., filter cakes, sludges).

9. **Process Integration:** Seamlessly fitting the mechanical separation unit into the overall plant flow scheme, considering upstream feeding mechanisms and downstream processing requirements.

5. Relevance to Petroleum Refining and Petrochemicals

Mechanical separation operations are pervasive throughout refineries and petrochemical complexes:

- **Catalyst Management:**
  - **Fluid Catalytic Cracking (FCC) Units: Cyclones are absolutely critical** for separating vast quantities of fine catalyst particles from the gaseous streams in both the reactor (to separate products from catalyst) and the regenerator (to separate flue gas from regenerated catalyst).
  - **Hydroprocessing/Polymerization:** Filtration or centrifugation is often used to **separate solid catalysts from liquid reaction products**.
  - **Catalyst Recovery/Recycling:** Mechanical separation methods (screening, elutriation, hydrocyclones) are used to classify catalyst particles, remove fines, or recover catalyst from wash waters.
- **Wastewater Treatment:**
  - **Primary Clarifiers:** Gravity sedimentation tanks are the first step to remove suspended solids from refinery effluent.
  - **Filters:** Various filters are used to polish treated wastewater before discharge.
  - **Centrifuges:** Used for dewatering the biological sludges generated in activated sludge units.

- **Oil-Water Separation:** Gravity settlers (e.g., API separators), coalescers, and centrifuges are used to separate oil from water streams, both for environmental discharge and oil recovery.
- **Product Purification:** Filtration to remove haze, waxes, or solid impurities from refined products (e.g., diesel, jet fuel) or petrochemicals (e.g., amorphous polymers, various chemical intermediates).
- **Dust Control:** Bag filters and cyclones are widely employed to capture particulate emissions from various operations, including flue gas from furnaces, power plants, and powder handling systems (e.g., carbon black production).
- **Sulfur Recovery:** Filtration of molten sulfur (produced from H2S in the SRU) for purification before solidification or shipment.
- **Coke Handling:** Screening of petroleum coke to classify it into different size fractions for various applications (e.g., anode coke, fuel coke).

4/ Posttest

- Define mechanical separation in your own words.
- Name three physical properties that are often used in mechanical separation.
- Give one example of mechanical separation and explain its principle.
- Why is mechanical separation important in industrial processes?

5/ Homework

- Think about your home. Can you identify two examples of mechanical separation that you use or see in your daily life? Describe them.

- Briefly explain the difference between sedimentation and centrifugation.

6/ References

- "Introduction to Chemical Engineering" by (mention a relevant textbook, e.g., McCabe, Smith, Harriott or a simpler equivalent).
- Lecture notes on Unit Operations.

Ministry of high Education and Scientific Research
Southern Technical University
Technological institute of Basra
Department of Chemical Industries Techniques

Learning package

In

Screen analysis

For

Students of First Year

By

Halah Kadhim Mohsin

Dep. Of Chemical industries Techniques

2025

1/ Overview

1/ A – Target Population: Technical institute students specializing in chemical technology, particularly those dealing with solid materials and powders.

1/ B – Rationale: To understand the method and importance of analyzing particle size distribution using screens, which is crucial for quality control and process design.

1/ C – Central Idea: Determining how much of a solid material falls into different size groups by passing it through a series of sieves with decreasing mesh sizes.

1/ D – Performance Objectives:

By the end of this lecture, students will be able to define screen analysis.

To explain the basic steps of performing a screen analysis.

- To understand why particle size distribution is important in industry.

2/ Pretest

- What tool do you use at home to separate spaghetti from water after cooking?
- If you have a mixture of big and small beads, how would you separate them by size?
- Why might a baker want flour to be very fine?

3/ Lecture

1. Introduction to Screen Analysis

Definition: Screen analysis, also known as sieve analysis or particle size analysis by sieving, is a fundamental method used to determine the particle size distribution of a granular material. It involves passing a sample of the material through a series of sieves (screens) with progressively smaller mesh openings. The material retained on each sieve is then weighed, allowing for the calculation of the percentage by weight of particles within specific size ranges.

Importance in Chemical Engineering: For chemical engineers, understanding particle size distribution is paramount across various unit operations and processes:

- **Reaction Kinetics & Reactor Design:** For heterogeneous reactions (e.g., solid catalysts in gas/liquid phase reactions), the surface area of the solid catalyst is critical. Finer particles offer larger surface area, enhancing reaction rates. However, too fine particles can increase pressure drop in fixed beds or lead to excessive entrainment in fluidized beds.
- **Mass Transfer:** Particle size influences diffusion rates, dissolution rates (e.g., dissolving a solid reactant), and adsorption capacity.
- **Fluid Flow & Pressure Drop:** In packed beds (e.g., fixed bed reactors, adsorption columns) or filtration media, particle size directly impacts bed permeability and thus pressure drop. Finer particles lead to higher resistance to fluid flow.
- **Material Handling & Storage:** Particle size affects flowability, segregation tendencies, dusting, and bulk density, which are crucial for designing hoppers, conveyors, and storage silos.

- **Separation Processes:** The efficiency of operations like filtration, sedimentation, and centrifugation is highly dependent on the size of the particles being separated.
- **Product Quality Control:** For many chemical products (e.g., pigments, pharmaceuticals, fertilizers, catalysts), particle size distribution is a key specification that affects properties like solubility, reactivity, strength, color, and consumer appeal.

2. Principles of Screen Analysis

The principle is straightforward:

1. A stack of standard sieves, arranged with the largest mesh opening at the top and the smallest at the bottom, is used. A collection pan is placed at the very bottom.
2. A known mass of the dry granular sample is placed on the top (largest) sieve.
3. The stack is agitated (manually or mechanically using a sieve shaker) for a specified period. This causes particles to fall through the sieves until they reach a sieve whose openings are smaller than the particle's smallest dimension.
4. The material retained on each sieve, and that collected in the pan, is then weighed.

Particle Size and Shape: Sieve analysis effectively measures the "minimum dimension" of a particle (the size of the square opening it can just pass through). For non-spherical particles, this might not accurately represent the particle's overall size or surface area, which is an important consideration for chemical engineers.

3. Data Representation & Interpretation

The results of screen analysis are typically presented in:

1. **Tabular Form:** Showing the mass retained on each sieve and the cumulative percentages.

2. **Graphical Form:**
    - **Histogram:** Showing the weight percentage of particles within each size range.
    - **Cumulative Plot (Oversize or Undersize):**
        - **Cumulative Percent Retained (Oversize):** Percentage of particles *larger* than a given sieve opening.
        - **Cumulative Percent Passing (Undersize):** Percentage of particles *smaller* than a given sieve opening. This is often the most useful plot for chemical engineers as it directly shows the fineness of the material.
    - **Log-Probability Plot:** Often used to check if the particle size distribution follows a normal or log-normal distribution, which can be useful for predicting behavior.

Key Parameters Derived:

- **Mean/Median Particle Size (D50):** The particle size at which 50% of the material is finer (or coarser).
- **Specific Surface Area:** While not directly measured, it can be estimated from particle size distribution, which is crucial for catalysts and adsorbents.
- **Modulus of Fineness:** An empirical measure of the fineness of a material, often used in civil engineering but adaptable.

4. Applications in Petroleum Refining & Chemical Industries

Screen analysis is vital for:

1. **Catalyst Characterization:**
    - **Fluid Catalytic Cracking (FCC):** The efficiency of FCC units (which use fluidized beds) critically depends on the particle size distribution of the FCC catalyst. Too many fines (<20μm) lead to excessive elutriation (loss from the reactor) and emission problems. Too many

coarse particles (>150μm) can lead to poor fluidization quality (slugging, channeling) and inefficient gas-solid contact. Screen analysis is routinely performed on fresh and equilibrium catalysts to monitor this.
    - **Hydrotreating/Hydrocracking (Fixed Bed):** Particle size of these catalysts affects the pressure drop across the reactor bed. If particles are too fine, the pressure drop can become excessive, requiring higher pumping power or leading to operational issues. Screen analysis ensures consistent packing density and flow characteristics.
    - **Catalyst Attrition:** Monitoring the generation of fines over time, which indicates catalyst attrition (breakdown) during operation.
2. **Powdered Product Quality Control:**
    - **Pigments & Dyes:** Particle size affects color strength, dispersion, and opacity.
    - **Pharmaceutical Powders:** Particle size directly impacts dissolution rates, bioavailability, and tablet compressibility.
    - **Fertilizers:** Particle size affects spreading uniformity, dissolution, and flowability.
3. **Raw Material Specification:** Ensuring incoming raw materials (e.g., powdered reagents, fillers) meet size specifications for downstream processing.
4. **Optimizing Separation Processes:**
    - **Filtration:** Knowing particle size helps select the appropriate filter medium pore size and predict filter cake formation and pressure drop.
    - **Sedimentation/Centrifugation:** Particle size and density are key parameters for predicting settling rates and designing clarifiers or centrifuges.
    - **Dust Collection:** Assessing the efficiency of cyclones or bag filters for removing specific particle sizes from vent gases.

5. **Process Monitoring & Troubleshooting:** Changes in particle size distribution during a process can indicate problems such as excessive grinding, crystallization issues, or agglomeration.

5. Limitations & Considerations for Chemical Engineers

- **Agglomeration:** Particles that stick together can skew results, appearing larger than their primary particle size. This is common with cohesive powders (e.g., highly hydroscopic materials, very fine particles). Pre-treatment (e.g., gentle dispersion) may be needed.
- **Particle Shape:** Sieve analysis assumes spherical particles effectively. For highly irregular or elongated particles, the "sieve size" may not correlate well with other particle properties (e.g., aerodynamic diameter, surface area).
- **Static Electricity:** Can cause fine particles to stick to sieve surfaces, leading to inaccurate weights.
- **Moisture Content:** Wet or damp particles will agglomerate and not pass through sieves accurately. Samples must be dry.
- **Method Sensitivity:** The duration and intensity of shaking can influence results. Standardization (e.g., using ASTM standards) is critical.
- **Limited Range:** Sieve analysis is typically effective for particles from about 20 µm up to several millimeters. For sub-micron particles, other techniques (e.g., laser diffraction, dynamic light scattering) are required.

6. Suggested Additions for Chemical Engineering Focus

- **Beyond Sieving:** Briefly introduce other particle size analysis techniques (e.g., laser diffraction, image analysis, sedimentation methods) and explain *when* a chemical engineer would choose these over sieving (e.g., for sub-micron particles, shape analysis, in-situ measurements).

- **Correlation with Process Performance:** Emphasize how changes in PSD affect *process yield, conversion, selectivity,* and *energy consumption* (e.g., grinding energy).
- **Statistical Analysis of PSD:** Touch upon basic statistical parameters like standard deviation and skewness to quantitatively describe a distribution.

Example Problem: Interpreting Screen Analysis Data (Chemical Engineering Focus)

Problem Statement: A fresh batch of catalyst for a fixed-bed hydrodesulfurization (HDS) reactor in a refinery underwent screen analysis. The results for a 500 g sample are as follows:

Sieve Mesh Size (µm)	Mass Retained (g)
1000	25
710	125
500	200
355	100
250	40
Pan (<250)	10

Export to Sheets

1. Calculate the weight percentage retained on each sieve.
2. Calculate the cumulative weight percentage passing through each sieve (cumulative undersize).
3. Based on the cumulative undersize data, what can a chemical engineer infer about the suitability of this catalyst batch if the design specification requires that **at least 90% of the catalyst must be larger than 355 µm** to ensure acceptable pressure drop across the reactor?

Solution Steps:

1. **Calculate Weight Percentage Retained on Each Sieve:**
   Total Sample Mass = $500\ g$

Sieve Mesh Size (µm)	Mass Retained (g)	% Retained (Mass Retained / Total Mass * 100)
1000	25	$25/500 \times 100 = 5\%$
710	125	$125/500 \times 100 = 25\%$
500	200	$200/500 \times 100 = 40\%$
355	100	$100/500 \times 100 = 20\%$
250	40	$40/500 \times 100 = 8\%$
Pan (<250)	10	$10/500 \times 100 = 2\%$
Total	**500**	**100%**

2. **Calculate Cumulative Weight Percentage Passing Through Each Sieve (Cumulative Undersize):**
   This means for a given sieve size, what percentage of the total sample passed *through* that sieve (and thus ended up on a smaller sieve or in the pan).

   - For 1000 µm sieve: % passing = $100\% - 5\% = 95\%$
   - For 710 µm sieve: % passing = $95\% - 25\% = 70\%$

1.

- For 500 µm sieve: % passing = $70\% - 40\% = 30\%$
- For 355 µm sieve: % passing = $30\% - 20\% = 10\%$
- For 250 µm sieve: % passing = $10\% - 8\% = 2\%$
- For Pan (<250 µm): % passing = 2% (all passed 250 µm sieve, so this is the final cumulative percentage).

Sieve Mesh Size (µm)	% Retained	Cumulative % Passing (Undersize)
1000	5	95
710	25	70
500	40	30
355	20	10
250	8	2
Pan (<250)	2	0 (All particles are <= 250um)

(Correction on Pan: The "Pan" collects particles smaller than the smallest sieve. So, 2% of particles are smaller than 250 µm).

Inference about Catalyst Suitability: The design specification requires that **at least 90% of the catalyst must be larger than 355 µm**. From our cumulative passing data:

- The percentage of catalyst **passing through 355 µm** sieve is **10%**.
- This means the percentage of catalyst **retained on (or larger than) 355 µm** is 100%−10%=90%.

Since exactly 90% of the catalyst is larger than 355 µm, this batch **meets the design specification** at the minimum acceptable level. A chemical engineer would likely approve this batch for use in the HDS reactor, assuming other specifications (e.g., chemical composition, mechanical strength) are also met. This specific particle size control is vital to ensure optimal pressure drop and avoid excessive energy consumption for pumping reactants through the fixed bed.

4/ Posttest

- What is the main goal of screen analysis?
- Describe the basic setup of sieves for a screen analysis test.
- Why is knowing the particle size distribution important for industrial products?
- If a material is described as "coarse," what does that mean about its particle size?

5/ Homework

1. **Relevance to Refining Operations:**
   - For a Fixed Bed Hydrocracking reactor in a refinery, explain in detail why the **particle size distribution of the catalyst** is critical. How does sieve analysis data help in managing (a) reactor pressure drop and (b) catalyst effectiveness (reaction rate)?

- In a typical Fluid Catalytic Cracking (FCC) unit, why is it undesirable to have an excessive amount of catalyst fines (particles < 20 µm)? How would screen analysis help a chemical engineer identify and address this issue?

2. **Data Interpretation & Application:**
   - A batch of a powdered additive for lubricant oils needs to have a particle size distribution where at least 75% of the particles are between 50 µm and 100 µm. If a sieve analysis yields a cumulative percent passing value of 20% at 100 µm and 10% at 50 µm, does this batch meet the specification? Justify your answer.
   - Why is ensuring the sample is completely dry critical before performing a sieve analysis on a highly hygroscopic (moisture-absorbing) chemical powder? What implications would a wet sample have on the results and their interpretation by a chemical engineer?
3. **Beyond Sieving:**
   - A chemical plant produces nanoparticles (typically < 100 nm) used as a catalyst support. Would sieve analysis be a suitable method to determine their particle size distribution? If not, suggest a more appropriate technique and explain its underlying principle.

6/ References

- "Unit Operations of Chemical Engineering" (standard textbook for fundamental processes).
- Online resources or videos explaining "Sieve Analysis" for practical understanding.

Ministry of high Education and Scientific Research
Southern Technical University
Technological institute of Basra
Department of Chemical Industries Techniques

Learning package

In

Sedimentation and thickening

For

Students of First Year

By

Halah Kadhim Mohsin

Dep. Of Chemical industries Techniques

2025

1/ Overview

1/ A – Target Population: Technical institute students specializing in chemical technology, environmental engineering, or industrial processes.

1/ B – Rationale: To understand the principles of sedimentation and thickening for separating solids from liquids, which are common in water treatment, mining, and chemical industries.

1/ C – Central Idea: Using gravity to separate heavier solid particles from a liquid, allowing them to settle at the bottom (sedimentation) and making the liquid clearer (clarification) or the solids more concentrated (thickening).

1/ D – Performance Objectives:

- By the end of this lecture, students will be able to define sedimentation and thickening.
- To explain the role of gravity in these processes.
- To identify basic applications of sedimentation and thickening.

2/ Pretest

- What makes an object sink or float in water?
- If you shake a bottle of water with dirt in it, and then leave it still, what happens to the dirt?
- What is the difference between a clear liquid and a muddy liquid?

3/ Lecture Content

1. Introduction to Sedimentation and Thickening

Definition:

- **Sedimentation:** A gravity-driven physical separation process used to separate solid particles from a fluid (liquid or gas) by allowing the particles to settle out due to their density difference from the fluid. The primary goal of sedimentation is often to obtain a clear supernatant liquid (clarification).
- **Thickening:** A specific application of sedimentation where the primary goal is to increase the concentration of the solid particles in the underflow slurry, thereby reducing the volume of the solid-liquid mixture. This is typically done to prepare the slurry for further dewatering processes (e.g., filtration, centrifugation) or for disposal.

Importance in Chemical Engineering and Petroleum Refining: Sedimentation and thickening are ubiquitous unit operations in process industries, particularly vital in chemical plants and refineries for:

- **Feedstock Purification:** Removing suspended solids from raw materials to protect downstream equipment (pumps, heat exchangers, reactors) from fouling, erosion, or catalyst poisoning.
- **Product Recovery & Concentration:** Concentrating valuable solid products from dilute slurries.
- **Wastewater Treatment:** A cornerstone of primary and sometimes secondary wastewater treatment in refineries and

chemical plants to remove suspended solids, oil droplets, and other contaminants before discharge or further biological treatment.

- **Sludge Dewatering:** Reducing the volume of waste sludges generated from various processes, making subsequent handling and disposal more economical.
- **Process Efficiency:** Improving the clarity of recycle streams or preparing feed for other separation units.

2. Fundamental Principles of Particle Settling

The effectiveness of sedimentation relies on the interplay of forces acting on individual particles and the collective behavior of particles in a concentrated suspension.

1. **Free Settling (Dilute Suspensions):**
    - **Principle:** Applies when particles are far enough apart that their settling is unaffected by other particles or by the vessel walls. The particles settle independently.
    -

- Stokes' Law (for small, spherical particles in laminar flow):

$$v_t = \frac{D_p^2(\rho_s - \rho_f)g}{18\mu}$$

  Where:

  - v_t = terminal settling velocity (m/s)
  - D_p = particle diameter (m)
  - ρ_s = solid particle density (kg/m^3)
  - ρ_f = fluid density (kg/m^3)
  - g = acceleration due to gravity (m/s^2)
  - μ = fluid viscosity (Pa·s)

- Chemical Engineering Significance: This equation highlights that settling velocity increases with particle size squared, density difference, and gravity, and decreases with fluid viscosity. For chemical engineers, this implies that heating a viscous slurry (to reduce μ) or forming larger aggregates (by flocculation) can significantly improve

1. settling.
2. **Hindered Settling (Concentrated Suspensions):**
   - **Principle:** Occurs when particles are close enough to interfere with each other's settling. The displaced fluid must flow through a restricted area, increasing drag and reducing the effective density difference. Particle-particle interactions also become significant. The settling rate is much lower than predicted by Stokes' Law.
   - **Zone Settling:** In batch hindered settling, distinct zones typically form:
     - **Zone A (Clear Liquid):** Supernatant liquid.
     - **Zone B (Constant Settling Rate Zone):** Particles settle at a constant, hindered velocity.
     - **Zone C (Transition Zone):** Particle concentration gradually increases.
     - **Zone D (Compression Zone):** Particles support each other, and further settling occurs by liquid being squeezed out from the pores between

compressed particles. This zone is crucial for thickening.

3. Equipment for Sedimentation and Thickening

1. **Gravity Settlers / Clarifiers:**
    - **Description:** Large, typically circular or rectangular tanks designed for continuous operation. Slurry is fed into a central feedwell, where its velocity is reduced to promote settling. Clear liquid overflows from a perimeter weir, and settled solids (sludge) are collected at the bottom.
    - **Circular Clarifiers (Most common):** Feature a slowly rotating rake mechanism at the bottom to gently push the settled sludge towards a central discharge cone.
    - **Rectangular Clarifiers:** Often used in multi-tank wastewater treatment plants.
    - **Design Considerations:** The key design parameter is the **surface area** of the tank, which determines the **overflow rate** (volume of liquid flowing out per unit area per unit time). This rate must be less than the settling velocity of the smallest particle to be removed.
    - **Applications in Refining:** Primary clarifiers in **wastewater treatment plants** to remove suspended solids, oil, and grease.
2. **API Separators (American Petroleum Institute Separators):**
    - **Description:** A specific type of gravity settler, typically rectangular, designed primarily for the separation of oil from water in refinery wastewater streams. They exploit the density difference between oil and water, with baffles and skimmers to aid separation.
    - **Principle:** Based on Stokes' Law for spherical droplets. Designed to remove oil droplets larger than a specified size (e.g., 150 µm).

- **Importance:** A primary physical treatment step in refinery wastewater systems, crucial for meeting discharge limits.

3. **Thickeners:**
   - **Description:** Similar in appearance to clarifiers (large circular tanks with rakes), but optimized for achieving a high concentration of solids in the underflow rather than clear overflow. They have a deeper sludge bed and slower rake mechanisms to aid compaction.
   - **Applications:** Concentrating sludges from various refinery processes (e.g., spent caustic treatment, tank bottom cleanouts) before dewatering (e.g., via filter presses).
4. **Lamella Clarifiers / Inclined Plate Settlers:**
   - **Description:** Consist of a series of inclined plates or tubes inside a tank. Slurry flows between the plates, and particles settle onto the plate surfaces, sliding down into a sludge hopper.
   - **Advantages:** Offers a much larger effective settling area within a significantly smaller footprint compared to conventional clarifiers. This is due to the short settling distance for particles.
   - **Applications:** Space-constrained areas, often used for upgrading existing clarifiers or for treating specific wastewater streams.

4. Chemical Engineering Design and Operational Considerations

1. **Mass Balances:** Fundamental for sizing clarifiers/thickeners. Calculating the mass flow rates of solids and liquids in the feed, overflow, and underflow streams.
2. **Batch Settling Tests:** Laboratory-scale tests (e.g., using a graduated cylinder) are essential to determine the actual settling characteristics of a specific slurry, including minimum

settling velocity, the onset of hindered settling, and the rate of compaction. This data is then scaled up for industrial design.

3. **Flocculation / Coagulation:**
    - **Chemical Significance:** Many fine particles (especially clays, silts, or oil droplets) have surface charges that prevent them from aggregating and settling. Chemical engineers use **coagulants** (e.g., aluminum sulfate, ferric chloride) to neutralize these charges, followed by **flocculants** (long-chain polyelectrolytes) to bridge the neutralized particles together, forming larger, faster-settling flocs.
    - **Impact:** This chemical pre-treatment dramatically improves settling rates and effluent clarity, significantly reducing the required size of sedimentation equipment. This is a crucial step in refinery wastewater treatment.
4. **Overflow Rate (Qo/A):** The critical design parameter for clarifiers. It's the maximum volumetric flow rate of clear liquid per unit area that can be achieved without entraining suspended solids.
5. **Solids Loading Rate:** For thickeners, the mass of solids fed per unit area per unit time is a key design parameter, ensuring the thickener can handle the incoming solids load and achieve the desired underflow concentration.
6. **Temperature Effects:** Changes in process fluid temperature directly impact viscosity and density, significantly affecting settling rates. Cooling a refinery wastewater stream, for example, would increase its viscosity and slow down settling.
7. **Sludge Rheology:** For thickened slurries, understanding their flow properties (often non-Newtonian) is critical for designing appropriate pumps and pipelines for underflow discharge.
8. **Environmental Regulations:** Meeting strict discharge limits for suspended solids and oil/grease in refinery effluent, making clarifier/separator performance paramount.

5. Challenges in Sedimentation and Thickening

- **Short-Circuiting:** Uneven flow patterns in the tank, leading to some fluid bypassing the settling zone.
- **Density Currents:** Differences in density of the incoming feed compared to the tank contents can cause density-driven flows that disrupt settling.
- **Floc Breakage:** Excessive turbulence in the feedwell or during rake movement can break fragile flocs, reducing settling efficiency.
- **Sludge Blanket Instability:** Upset conditions can cause the sludge blanket to rise or become unstable, leading to solids carry-over in the overflow.
- **Sludge Compaction:** For highly compressible sludges, achieving high underflow concentration can be challenging.

Example Problem: Clarifier Sizing for Refinery Wastewater

Problem Statement: A refinery's wastewater treatment plant needs to design a primary circular clarifier to remove suspended solids from its effluent. Batch settling tests on the wastewater show that the average hindered settling velocity for the solids is 0.0005 m/s. The desired overflow rate is 0.0004 m/s (to ensure adequate settling). The wastewater flow rate to the clarifier is 500 m3/h.

Calculate the required diameter of the circular clarifier.

Given Data:

- Average hindered settling velocity (v_s) = $0.0005\ \mathrm{m/s}$
- Desired overflow rate (v_{design}) = $0.0004\ \mathrm{m/s}$ (This is the design superficial velocity, which should be less than the actual settling velocity to ensure particles settle)
- Wastewater flow rate (Q) = $500\ \mathrm{m^3/h}$

Solution Steps:

1. Convert Flow Rate to Consistent Units:
   The design velocity is in m/s, so convert the flow rate from m^3/h to m^3/s:
   $Q = 500 \frac{\mathrm{m^3}}{\mathrm{h}} \times \frac{1\ \mathrm{h}}{3600\ \mathrm{s}} = 0.1389\ \mathrm{m^3/s}$
2. Determine Required Surface Area (A):
   The overflow rate (which is essentially the volumetric flow rate divided by the surface area) should be less than or equal to the settling velocity of the smallest particle you want to remove. Therefore, the required surface area is based on the *design overflow rate*:

$$A = \frac{Q}{v_{design}}$$

$$A = \frac{0.1389 \text{ m}^3/\text{s}}{0.0004 \text{ m/s}}$$

$$A = 347.25 \text{ m}^2$$

3. **Calculate the Diameter (D) for a Circular Clarifier:**
   For a circular area, $A = \frac{\pi D^2}{4}$.
   So, $D^2 = \frac{4A}{\pi}$

$$D^2 = \frac{4 \times 347.25 \text{ m}^2}{\pi}$$

$$D^2 = \frac{1389}{\pi}$$

$$D^2 \approx 442.1 \text{ m}^2$$

$$D = \sqrt{442.1}$$

$$D \approx 21.03 \text{ m}$$

Answer: The required diameter of the circular clarifier is approximately **21.03 meters**. This diameter ensures that the design overflow rate is maintained, allowing sufficient time for suspended solids to settle from the refinery wastewater.

4/ Posttest

- Define sedimentation and thickening. What is the primary goal of each?
- How does gravity play a role in sedimentation?
- Name two factors that can affect how fast particles settle in a liquid.
- Give two examples of industrial applications where sedimentation or thickening is used.

5/ Homework

1. **Refinery Application Analysis:**
    - Discuss the critical role of **API separators** in petroleum refinery wastewater treatment. Explain how their design principles (specifically related to oil droplet size and density difference) are applied to achieve efficient oil-water separation. Why is this separation crucial before further treatment steps?
    - In a desalter unit, crude oil is mixed with wash water to remove salts. The subsequent separation of the brine/water phase from the oil phase relies heavily on gravity sedimentation. What factors (from a chemical engineering perspective, considering crude oil properties) might hinder this separation, and what operational adjustments can be made to improve it?
2. **Design and Operational Challenges:**
    - Distinguish between "free settling" and "hindered settling." Why is the concept of hindered settling particularly important for designing **thickeners** in chemical plants, and how does it influence the required size of the equipment compared to a clarifier with similar flow rates?

    - You are operating a clarifier in a chemical plant, and you notice a significant increase in suspended solids in the overflow. What are three potential chemical engineering reasons for this issue, and what immediate corrective actions would you consider?
3. **Chemical Aids in Sedimentation:**
    - Explain the mechanism by which **flocculants** improve the efficiency of sedimentation. Why are flocculants almost universally used in industrial wastewater clarifiers, especially in refinery applications where colloidal particles and oil droplets might be present?

6/ References

- "Principles of Unit Operations" (a good reference for fundamental concepts).
- "Water and Wastewater Engineering" (for specific applications in water treatment).

Ministry of high Education and Scientific Research
Southern Technical University
Technological institute of Basra
Department of Chemical Industries Techniques

Learning package
In
Centrifuge

For

Students of First Year

By

Halah Kadhim Mohsin

Dep. Of Chemical industries Techniques
2025

1/ Overview

1/ A – Target Population: Technical institute students specializing in chemical technology, biotechnology, or industrial processes.

1/ B – Rationale: To understand the principles and applications of using centrifugal force for separating components in various industrial and laboratory settings.

1/ C – Central Idea: Utilizing rapid rotation to generate a powerful centrifugal force, which accelerates the separation of materials (solids from liquids, or liquids of different densities) that would normally separate slowly by gravity.

1/ D – Performance Objectives:

- By the end of this lecture, students will be able to define centrifugation.
- To explain the basic principle of how a centrifuge works.
- To identify common applications of centrifuges in industry and daily life.

2/ Pretest

- When you ride a merry-go-round very fast, which way do you feel pushed?
- If you stir a cup of sugar and water, and the sugar dissolves, can you separate them by just spinning the cup? Why or why not?

What is "gravity"?

3/ Lecture

1. Introduction to Centrifugation

Definition: Centrifugation is a mechanical separation process that utilizes centrifugal force to separate components of a mixture based on differences in density. By rapidly rotating the mixture, a centrifugal field is generated, which is many times stronger than gravity. This artificial gravitational field accelerates the separation of phases (solid-liquid, liquid-liquid, or solid-liquid-liquid) that would otherwise settle very slowly or not at all under normal gravitational conditions.

Importance in Chemical Engineering and Petroleum Refining: Centrifugation is a powerful and often indispensable unit operation in the chemical and refining industries, particularly when:

- **High Separation Efficiency is Required:** For very fine particles (colloids, sub-micron) or for breaking stable emulsions where gravity settling is ineffective.
- **Rapid Separation is Needed:** To achieve high throughputs or for time-sensitive processes.
- **High Purity/Clarity is Desired:** To meet stringent product specifications or environmental discharge limits.
- **Valuable Solids/Liquids are Recovered:** Maximizing the yield of precious products or catalysts.

2. Principle of Centrifugation

The fundamental principle relies on the generation of centrifugal force (F_c):

$$F_c = m\omega^2 r$$

Where:

- m = mass of the particle/droplet
- ω = angular velocity of rotation (radians/second)
- r = radius from the center of rotation

This centrifugal force effectively replaces the gravitational force ($F_g = mg$). The ratio of centrifugal force to gravitational force is known as the **G-force** or **separation factor**:

$$\text{G-force} = \frac{F_c}{F_g} = \frac{m\omega^2 r}{mg} = \frac{\omega^2 r}{g}$$

1. A higher G-force means a faster separation. Modern centrifuges can achieve G-forces ranging from a few hundreds to tens of thousands.

The settling velocity of a particle/droplet in a centrifugal field can be derived by modifying Stokes' Law:

$$v_r = \frac{D_p^2(\rho_p - \rho_f)\omega^2 r}{18\mu}$$

Where v_r is the radial settling velocity, D_p is particle/droplet diameter, ρ_p is particle/droplet density, ρ_f is fluid density, and μ is fluid viscosity.

This equation shows that the settling rate is directly proportional to the square of the particle diameter, the density difference, and the G-force, and inversely proportional to the fluid viscosity.

3. Classification of Centrifuges

Centrifuges can be broadly classified into two main types based on their separation mechanism:

A. Sedimenting Centrifuges (for solid-liquid or liquid-liquid separation by density)
These units allow denser components to settle outwards against the bowl wall, and lighter components to move inwards.

Tubular Bowl Centrifuge:

- **Description:** A tall, narrow cylinder rotating at very high speeds (up to 50,000 rpm). Feed enters from the bottom, and the separated liquid phases (or liquid and settled

solids) exit from the top. Solids accumulate on the bowl wall and must be manually removed (batch or semi-continuous).
    - **Advantages:** Generates extremely high G-forces, excellent for separating very fine solids from liquids (clarification) or breaking stable emulsions.
    - **Disadvantages:** Low solids holding capacity, batch removal of solids (high labor for solid removal), not suitable for high solids concentration.
    - **Applications in Refining/Chemical:** Polishing of lubricating oils, fuel oils, separation of catalyst fines in very dilute slurries, removal of haze from vegetable oils, purification of pharmaceutical fermentation broths.
2. **Disk-Stack Centrifuge (Centrifugal Separator):**
    - **Description:** Consists of a stack of conical disks within the rotating bowl. The disks provide a large equivalent settling area, significantly reducing the settling distance for particles/droplets. Feed enters from the top, flows through distribution holes in the disks, and separates into light and heavy phases. Solids accumulate on the bowl wall or are discharged intermittently (self-cleaning types).
    - **Advantages:** High capacity for liquid-liquid and liquid-solid separation, very efficient for breaking emulsions and clarifying liquids, can be designed for continuous automatic discharge of solids.
    - **Disadvantages:** More complex design than tubular bowls, can be sensitive to large or abrasive particles.
    - **Applications in Refining/Chemical: Crucial for breaking oil-water emulsions in refineries (e.g., desalters, slop oil recovery, tank bottom treatment)**. Also used for purification of fuels (e.g., marine diesel, jet fuel), vegetable oils, and fermentation broths.
3. **Solid Bowl Decanter Centrifuge (Conical Bowl Centrifuge):**

- **Description:** A horizontal, conical-cylindrical bowl with an internal screw conveyor that rotates at a slightly different speed than the bowl. The conveyor continuously scrapes settled solids from the bowl wall and moves them towards the conical end for discharge, while the clarified liquid overflows from the cylindrical end.
- **Advantages:** Fully continuous operation, handles high solids concentrations (slurries), produces relatively dry cake, flexible for varying feed characteristics.
- **Disadvantages:** Lower G-forces than tubular/disk-stack centrifuges, may not achieve highest liquid clarity.
- **Applications in Refining/Chemical: Dewatering of various sludges (e.g., wastewater treatment sludges from API separators, DAF units, biological treatment), concentration of catalyst slurries (e.g., from heavy oil upgrading processes, some polymerization processes), treatment of drilling muds.**

B. Filtering Centrifuges (for solid-liquid separation by filtration) These units have a perforated basket lined with a filter medium (cloth or screen). Liquid passes through the medium under centrifugal force, while solids are retained.

1. **Basket Centrifuge (Perforated Basket):**
   - **Description:** Can be batch or continuous. The rotating basket has a perforated wall. Feed slurry is introduced, liquid drains through the filter medium, and solids are retained on the basket wall. Solids can be washed and then scraped off (batch) or discharged continuously (pusher type).
   - **Advantages:** Produces a very dry filter cake, efficient washing of solids, good for crystalline or granular solids.

- **Disadvantages:** Batch operation often requires manual labor, potential for fine particle loss through filter medium.
- **Applications in Refining/Chemical:** Separation of crystalline products (e.g., salts, sugar, plastics), dewatering of granular catalyst particles, separation of fine chemicals.

4. Applications in Petroleum Refining and Chemical Industries (Detailed)

- **Refinery Emulsion Breaking & Water Treatment:**
  - **Crude Oil Desalting:** While electrostatic desalters are common, centrifuges can be used for challenging emulsions or as polishing steps.
  - **Slop Oil Recovery:** Separating oil, water, and solids from slop oil streams to recover valuable hydrocarbons and reduce waste.
  - **Wastewater Treatment:** Particularly for secondary and tertiary treatment, to remove fine oil droplets, suspended solids, and biological floc from effluent (e.g., after DAF or activated sludge units).
- **Catalyst Management:**
  - **Spent Catalyst Recovery/Dewatering:** Decanter centrifuges are used to dewater slurries of spent catalyst particles from various processes (e.g., from heavy oil hydroprocessing or other slurry-phase reactors) before regeneration or disposal.
  - **Catalyst Preparation:** Used in chemical manufacturing to separate and wash catalyst precursors or final catalyst particles.
- **Fuel and Lubricant Purification:**
  - **Diesel/Jet Fuel Polishing:** Removing trace water and solid particulates to meet strict fuel quality standards and prevent damage to engines.

    - **Lubricating Oil Purification:** Removing solid contaminants, water, and insoluble impurities to extend oil life and ensure performance.
- **Bitumen/Heavy Oil Upgrading:** Separation of asphaltenes or other heavy, dense components from lighter fractions.
- **Polymer and Fine Chemical Production:** Separation and washing of solid polymer particles or fine chemical crystals from reaction mixtures or slurries.

5. Chemical Engineering Design & Operational Considerations

- **Fluid & Particle/Droplet Properties:**
    - **Density Difference ($\rho p - \rho f$):** The primary driving force. Centrifuges are powerful when this difference is small.
    - **Viscosity (μ):** High viscosity significantly hinders separation. Heating the feed to reduce viscosity is a common chemical engineering strategy.
    - **Particle/Droplet Size (Dp):** Centrifuges excel at separating very fine particles/droplets that defy gravity settling.
    - **Solids Concentration:** Dictates the choice of centrifuge (e.g., clarifier/disk-stack for dilute, decanter for concentrated).
- **G-force and Sigma Factor (Σ):**
    - **G-force:** Determined by rotational speed (ω) and bowl radius (r). Higher G-force generally leads to faster separation or better resolution.
    - **Sigma Factor (Σ):** A theoretical "equivalent settling area" that allows for comparison and scale-up of different continuous centrifuges. It is a machine characteristic, independent of the fluid properties. For a given separation duty, the required Σ is calculated, and then a centrifuge with that Σ (or greater) is selected.
- **Materials of Construction:** Crucial due to high rotational speeds (stress), abrasive solids, and corrosive nature of many

chemical and refinery streams (e.g., presence of sulfur compounds, acids, or caustics). Stainless steels and specialized alloys are common.
- **Temperature & Pressure:** Operating conditions must be maintained for optimal separation (e.g., to control viscosity or prevent flashing of volatile components).
- **Automation & Control:** Many modern centrifuges are fully automated with continuous discharge and clean-in-place (CIP) systems, important for continuous chemical processes.
- **Maintenance & Safety:** High-speed rotating equipment requires precision balancing and regular maintenance to prevent catastrophic failure. Proper guarding and interlocks are essential due to flammable/toxic materials. Vibration monitoring is critical.

6. Suggested Additions for Chemical Engineering Focus

- **Economic Evaluation:** Brief discussion on capital cost vs. operating cost trade-offs compared to other separation methods (e.g., filtration).
- **Integration into Process Flow Diagrams (PFDs):** How centrifuges are positioned within a larger refinery or chemical process, showing their connections to upstream and downstream units.
- **Troubleshooting:** Common operational problems (e.g., poor separation, vibration, plugging) and their chemical engineering solutions.

Example Problem: Centrifuge Selection for Catalyst Fines in a Refinery

Problem Statement: A new heavy oil upgrading process in a refinery produces a dilute slurry containing very fine, valuable catalyst particles (density = 2800 kg/m3, average diameter = 5 µm) suspended in a viscous hydrocarbon liquid (density = 850 kg/m3, viscosity = 0.005 Pa·s at operating temperature). The refinery needs

to continuously recover these catalyst fines with high efficiency to minimize loss and prevent downstream fouling. Gravity settling is too slow.

Which type of centrifuge would be most suitable for this application, and why?

Solution Approach:

1. **Analyze Slurry Characteristics and Requirements:**
    - **Material:** Very fine catalyst particles (5 µm), density higher than liquid.
    - **Liquid:** Viscous hydrocarbon liquid.
    - **Concentration:** Dilute slurry (implies primary goal is clarification or recovery of solids from a large liquid volume).
    - **Requirement:** Continuous recovery of *valuable* fines with *high efficiency*. Gravity settling is too slow.
2. **Evaluate Centrifuge Types based on Characteristics:**
    - **Tubular Bowl Centrifuge:**
        - **Pros:** Generates very high G-forces, excellent for very fine particles and clarification.
        - **Cons:** Low solids holding capacity, batch or semi-continuous solids removal. This is a continuous process, and continuous fines recovery is needed. While high G-force is good, manual solid removal is a drawback for continuous, large-scale operation.
    - **Disk-Stack Centrifuge:**
        - **Pros:** High capacity, very efficient for fine particle separation and clarification, can have automatic, intermittent solids discharge ("self-cleaning" type). Large equivalent settling area from the disks.

        - **Cons:** Can be sensitive to abrasive particles (though catalyst fines might be fine enough), and very high viscosity can still be an issue.
    - **Solid Bowl Decanter Centrifuge:**
        - **Pros:** Fully continuous, handles high solids concentration.
        - **Cons:** Lower G-forces compared to disk-stack/tubular, might not be efficient enough for *very fine* (5 µm) particles in a *dilute* slurry if very high clarity/recovery is needed. More suited for dewatering concentrated sludges.
    - **Filtering Centrifuges (Basket, Pusher, etc.):**
        - **Cons:** These rely on a filter medium. 5 µm particles, especially if they are irregular or sticky, might blind the filter medium quickly or pass through. They are generally better for larger, more crystalline particles. Also, continuous discharge of such fine solids as a dry cake might be challenging with these types.
3. **Conclusion & Justification:**

    The **Disk-Stack Centrifuge (with self-cleaning capability)** is the most suitable choice for this application.

    - **High Efficiency for Fine Particles:** Its large effective settling area (due to the disk stack) and ability to generate high G-forces make it highly effective for continuously separating very fine, valuable catalyst particles (5 µm) from the dilute slurry.
    - **Continuous Operation & Solids Discharge:** Modern disk-stack centrifuges can operate continuously with automated, intermittent discharge of accumulated solids, meeting the "continuous recovery" requirement without significant downtime for manual cleaning.

- **Viscosity Handling:** While the liquid is viscous, heating the feed (a common practice in refining) can reduce viscosity, allowing the disk-stack centrifuge to perform effectively.

The primary alternative, a Decanter centrifuge, might struggle with the very fine particle size and dilute nature of the slurry if ultimate clarity/recovery is paramount. Tubular bowls offer higher G-force but are less practical for continuous, large-scale operation requiring frequent solids removal.

4/ Posttest

- What is the main force used in a centrifuge for separation?
- Explain, in simple terms, how a centrifuge separates a mixture of solids and liquids.
- Name two advantages of using a centrifuge over simple sedimentation.
- Give two examples of where centrifuges are used in industry or daily life.

5/ Homework

1. **Refinery Specific Application:**
   - Beyond general wastewater treatment, describe a specific scenario within a petroleum refinery (e.g., associated with FCC, hydrocracking, or crude oil processing) where a **Disk-Stack Centrifuge** would be specifically selected over a conventional gravity clarifier or a decanter centrifuge for separation. Justify your choice based on the nature of the mixture and separation goals.

- A refinery generates significant quantities of oily sludge from tank bottoms, which is a mix of oil, water, and solid particulates. Which type of centrifuge would typically be chosen for dewatering and separating these components to recover valuable oil, and why?

2. **Design Principles & Operating Parameters:**
    - Explain the concept of **G-force** in centrifugation. If you want to increase the G-force of a centrifuge, what two operational parameters can you adjust? How would increasing the G-force impact the separation of fine particles from a viscous liquid?
    - For a chemical process involving the separation of fine, suspended impurities from a high-viscosity product, a chemical engineer considers using a centrifuge. What primary engineering strategy related to the fluid properties can be employed to improve the centrifuge's performance without changing the centrifuge itself, and why does this strategy work?
3. **Comparative Analysis:**
    - Compare the **advantages and disadvantages** of using a **centrifuge** versus a **filter press** for the dewatering of a concentrated slurry of catalyst particles. Discuss this from the perspective of cake dryness, continuous operation, and handling very fine particles.

6/ References

- "Unit Operations of Chemical Engineering" (for detailed principles and equipment).
- Online resources from centrifuge manufacturers or educational videos on "how a centrifuge works."

Ministry of high Education and Scientific Research
Southern Technical University
Technological institute of Basra
Department of Chemical Industries Techniques

Learning package

In

Cyclone

For

Students of First Year

By

Halah Kadhim Mohsin

Dep. Of Chemical industries Techniques

2025

1/ Overview

1/ A – Target Population: Technical institute students specializing in chemical technology, environmental control, or industrial processes.

1/ B – Rationale: To understand the design and operation of cyclone separators, which are essential devices for removing solid particles from gas streams in many industries.

1/ C – Central Idea: Using a swirling (vortex) gas flow to create centrifugal force, which pushes heavier solid particles to the wall of a conical chamber, allowing them to fall out of the gas stream.

1/ D – Performance Objectives:

- By the end of this lecture, students will be able to define a cyclone separator.
- To explain the basic working principle of a cyclone.
- To identify common applications of cyclones in industry.

2/ Pretest

- What happens if you try to spin a ball on a string and then let go? Which way does the ball fly?
- If you have air mixed with tiny dust particles, how could you separate the dust?
- Why is it bad for factories to release a lot of dust into the air?

3/Lecture Content

1. Introduction to Cyclone Separators

Definition: A cyclone separator is a simple, mechanical device used for the continuous removal of solid particulates (or sometimes liquid droplets) from a gas or liquid stream. It achieves separation by creating a centrifugal force field within a cylindrical or conical chamber, which causes denser particles to move outwards and fall out of the gas stream.

Importance in Chemical Engineering and Petroleum Refining: Cyclones are invaluable unit operations in chemical processes and refineries due to their:

- **Simplicity and Robustness:** No moving parts, relatively low maintenance.
- **Ability to Handle High Temperatures and Corrosive Environments:** Critical for many refinery processes.
- **Efficiency for Particle Recovery and Emission Control:** Key for recovering valuable catalysts or products and reducing particulate emissions to meet environmental regulations.
- **Protection of Downstream Equipment:** Preventing fouling, erosion, or blinding of heat exchangers, compressors, and catalyst beds.

2. Principle of Operation

The separation in a cyclone relies on the interplay of several forces:

1. **Tangential Entry:** The dirty gas stream enters the cylindrical upper section of the cyclone tangentially (horizontally) at high velocity.

2. **Outer Vortex (Downward Spiral):** This tangential entry creates a strong rotating (vortex) flow. The gas spirals downwards along the outer wall of the cyclone.
3. **Centrifugal Force:** Due to the high rotational velocity, particles within the gas stream experience a centrifugal force pulling them towards the outer wall. This force is proportional to the particle's mass, the square of the gas velocity, and inversely proportional to the radius of curvature.
4. **Inertial Separation:** Denser and larger particles, having more inertia, cannot follow the sharp curvature of the gas stream. They are flung outwards against the cyclone wall.
5. **Gravitational Force & Wall Friction:** Once at the wall, particles lose momentum and slide downwards due to gravity and some frictional drag from the gas, collecting in the dust hopper at the bottom.
6. **Inner Vortex (Upward Spiral):** As the gas approaches the conical section's apex, the direction of the vortex reverses. The cleaned gas forms an inner vortex, spiraling upwards and exiting through a central pipe (called the vortex finder) at the top of the cyclone.

3. Key Design Parameters and Performance Metrics

For a chemical engineer, understanding these parameters is crucial for selecting and evaluating cyclone performance:

1. **Cut Diameter (Dpc or D50):** This is the most critical characteristic of a cyclone. It represents the particle size for which the collection efficiency is 50%. In other words, 50% of particles of this size will be captured, and 50% will escape.
    - **Significance:** A smaller cut diameter indicates a more efficient cyclone for finer particles.
    - **Factors affecting Dpc:** Inlet gas velocity (higher velocity, smaller Dpc), cyclone diameter (smaller diameter, smaller Dpc), gas viscosity (lower viscosity,

smaller Dpc), particle density (higher density, smaller Dpc).

2. **Collection Efficiency (η):** The percentage of particles (or mass of particles) removed from the gas stream. It's usually reported as a function of particle size. An efficiency curve typically shows that efficiency increases sharply with increasing particle size.
3. **Pressure Drop (ΔP):** The energy loss associated with moving the gas through the cyclone. A higher pressure drop means more energy consumption by the fan or compressor. There's often a trade-off: higher gas velocity (for better efficiency and smaller Dpc) leads to higher pressure drop.
4. **Cyclone Geometry:** The relative dimensions of the cyclone (inlet area, body diameter, cone length, vortex finder diameter and length, dust outlet diameter) significantly influence its performance. Standard designs (e.g., Stairmand, Lapple) have optimized these ratios.

4. Factors Affecting Performance (Chemical Engineering Perspective)

- **Particle Properties:**
  - **Size Distribution:** Cyclones are generally effective for particles larger than 5-10 µm. Efficiency drops sharply for smaller particles.
  - **Density:** Denser particles are easier to separate.
  - **Shape:** Irregular shapes can affect drag forces.
  - **Stickiness/Agglomeration:** Cohesive particles can stick to walls or agglomerate, affecting flow and collection.
- **Gas Properties:**
  - **Inlet Velocity:** Higher tangential velocity improves centrifugal force and efficiency, but increases pressure drop and potential for erosion.

    - **Viscosity and Density:** Affect drag forces and particle terminal velocity. Gas temperature influences these properties.
- **Solids Loading:** High dust concentrations can sometimes improve efficiency due to particle-particle interactions, but can also lead to plugging or erosion.
- **Internal Flow Patterns:** Turbulent eddies, short-circuiting, and re-entrainment of collected dust can reduce efficiency.

5. Applications in Petroleum Refining (Crucial Role)

Cyclones are indispensable in petroleum refineries, especially in processes involving solid catalysts:

1. **Fluid Catalytic Cracking (FCC) Units:** This is the most prominent application. FCC units convert heavy petroleum fractions into lighter, more valuable products using a powdered catalyst in a fluidized bed.
    - **Reactor Cyclones (Primary & Secondary):** Located directly above the reactor riser (where the cracking reaction occurs). Their primary function is to efficiently separate the entrained catalyst particles from the hydrocarbon product vapor stream.
        - **Why critical?** Recovers valuable catalyst for regeneration, prevents catalyst fines from contaminating the cracked product (gasoline, diesel), and protects downstream equipment (fractionation columns, heat exchangers, compressors) from erosion and fouling.
    - **Regenerator Cyclones (Primary & Secondary):** Located in the regenerator vessel (where coke on the catalyst is burned off). They separate the regenerated catalyst particles from the hot flue gas (combustion products).

    - **Why critical?** Recovers the regenerated catalyst for recycle back to the reactor, thus maintaining catalyst inventory. Also crucial for reducing particulate emissions (catalyst fines) from the regenerator stack to meet stringent environmental air quality regulations.
2. **Delayed Coking Units:** Used to separate coke fines from the vapor effluent stream leaving the coke drums before they enter the fractionator. This prevents fouling and erosion downstream.
3. **Ash/Dust Removal from Fuel Gas:** Used to clean up fuel gas streams (e.g., from gasifiers or combustion units) before feeding them to burners or gas turbines, preventing erosion and fouling.
4. **Catalyst Handling Systems:** Employed in pneumatic conveying systems for catalysts to separate catalyst from the conveying gas before storage or feeding to reactors.

6. Advantages for Chemical Engineering Applications

- **Cost-Effective:** Relatively low capital and operating costs compared to more sophisticated collectors.
- **Simple Construction:** No moving parts, leading to high reliability and low maintenance requirements.
- **High Temperature and Pressure Capability:** Can operate effectively under the harsh conditions prevalent in many refinery and chemical processes.
- **Dry Collection:** Solids are collected dry, simplifying disposal or recycle.
- **Compact Footprint:** Relatively small physical size for the volume of gas handled.

7. Disadvantages

- **Limited Efficiency for Fine Particles:** Not effective for sub-micron particles or particles smaller than 5-10 µm. For high

efficiency on fine particles, cyclones are often used as a pre-cleaner before bag filters or electrostatic precipitators.

- **High Pressure Drop:** Higher efficiency usually comes with higher energy consumption due to increased pressure drop.
- **Erosion:** Highly abrasive particles can cause significant wear on cyclone walls, especially in the conical section and near the inlet.
- **Sensitive to Flow Rate Changes:** Performance drops off significantly if the gas flow rate deviates much from the design point.

Example Problem: Cyclone Performance in an FCC Unit

Problem Statement:
In an FCC unit, a set of primary cyclones in the reactor section is designed to separate catalyst particles from hydrocarbon vapors. The catalyst particles have an average density (ρ_s) of $1500\ \text{kg/m}^3$. The product vapor has a density (ρ_f) of $2\ \text{kg/m}^3$ and a viscosity (μ) of $2.5 \times 10^{-5}\ \text{Pa} \cdot \text{s}$ at operating conditions. The cyclones are designed for an inlet velocity of $20\ \text{m/s}$ and a characteristic cyclone diameter (D_c) of $1.5\ \text{m}$. Assume a constant K value of 0.05 for this specific cyclone design (relating to the number of effective turns, typical for a standard cyclone).

Estimate the theoretical cut diameter (D_{pc}) for this cyclone.

Formula for Cut Diameter (Lapple or similar approximation):
A common simplified formula for cyclone cut diameter is:

$$D_{pc} = \sqrt{\frac{9\mu D_c}{2\pi N_e v_i (\rho_s - \rho_f)}}$$

Where:

1.
- D_{pc} = cut diameter (m)
- μ = gas viscosity (Pa·s)
- D_c = cyclone body diameter (m)
- N_e = number of effective turns the gas makes in the cyclone (often empirical, typically between 1 to 10 for standard cyclones). A common simplified form sometimes uses a constant K such that $K = \frac{1}{2\pi N_e}$. If given K, use $D_{pc} = \sqrt{\frac{9\mu D_c K}{v_i(\rho_s - \rho_f)}}$.
- v_i = inlet gas velocity (m/s)
- ρ_s = particle density (kg/m^3)
- ρ_f = gas density (kg/m^3)

Let's use a common form relating to N_e, and then interpret the K value. If K is given as 0.05, it implies a simplified constant, let's proceed with that.
Let's use a simpler form where N_e is implicit or the formula is simplified by incorporating constants:
A more generalized simplified formula is:
$$D_{pc} = C\sqrt{\frac{\mu D_c}{v_i(\rho_s - \rho_f)}}$$If $K = 0.05$ is provided as a coefficient that encapsulates other constants and geometry, it could be used as:

$$D_{pc} = K\sqrt{\frac{\mu D_c}{v_i(\rho_s - \rho_f)}}$$

This simplified formula (often derived from balancing centrifugal and drag forces) assumes K is an empirical constant for a given cyclone design.

Given Data:

- Particle density (ρ_s) = $1500\ \mathrm{kg/m^3}$
- Fluid (vapor) density (ρ_f) = $2\ \mathrm{kg/m^3}$
- Fluid viscosity (μ) = $2.5 \times 10^{-5}\ \mathrm{Pa \cdot s}$
- Inlet velocity (v_i) = $20\ \mathrm{m/s}$
- Cyclone diameter (D_c) = $1.5\ \mathrm{m}$ (Assume this is the relevant diameter for the calculation, often D_body).
- Empirical constant $K = 0.05$ (dimensionless, a simplification).

Solution Steps:

1. **Calculate the density difference:**
   $\rho_s - \rho_f = 1500 - 2 = 1498\ \mathrm{kg/m^3}$
2. **Substitute values into the formula:**
   $$D_{pc} = 0.05\sqrt{\frac{(2.5 \times 10^{-5}\ \mathrm{Pa \cdot s}) \times (1.5\ \mathrm{m})}{(20\ \mathrm{m/s}) \times (1498\ \mathrm{kg/m^3})}}$$
3. **Perform calculations:**
   Numerator inside square root: $2.5 \times 10^{-5} \times 1.5 = 3.75 \times 10^{-5}$
   Denominator inside square root: $20 \times 1498 = 29960$
   Fraction inside square root: $\frac{3.75 \times 10^{-5}}{29960} \approx 1.2516 \times 10^{-9}$
   Square root: $\sqrt{1.2516 \times 10^{-9}} \approx 3.538 \times 10^{-5}\ \mathrm{m}$
4. **Calculate D_{pc}:**
   $$D_{pc} = 0.05 \times (3.538 \times 10^{-5}\ \mathrm{m})$$
   $$D_{pc} \approx 1.769 \times 10^{-6}\ \mathrm{m}$$

Convert to micrometers (µm): $D_{pc} \approx 1.769\ \mu\mathrm{m}$

Answer: The estimated theoretical cut diameter (Dpc) for this cyclone is approximately **1.77 µm**. This means that particles larger than approximately 1.77 µm have a greater than 50% chance of being collected, which is a very good performance for an FCC reactor cyclone, indicating high efficiency for catalyst fines recovery.

4/ Posttest

- What is the main purpose of a cyclone separator?
- Describe the path of the dusty gas and the separated particles inside a cyclone.
- Name two factors that affect how well a cyclone works.
- Give two examples of industries where cyclone separators are commonly used.

5/ Homework

1. **Role in Refinery Process Safety & Efficiency:**
    - Explain in detail the critical function of **reactor cyclones** and **regenerator cyclones** within a Fluid Catalytic Cracking (FCC) unit. From a chemical engineering perspective, discuss how their efficient operation impacts:
        - a) The economic viability of the FCC process (catalyst cost).
        - b) Environmental compliance (air emissions).
        - c) The long-term operability and maintenance of downstream equipment (e.g., fractionators, compressors).
2. **Troubleshooting & Optimization:**

- A chemical engineer observes a sudden increase in particulate emissions from the stack of a refinery's FCC regenerator, even though the flue gas flow rate appears normal. What are three potential reasons related to the **regenerator cyclones** that could explain this observation, and what initial troubleshooting steps would you recommend?
- How would increasing the inlet gas velocity to a cyclone separator affect its collection efficiency and pressure drop? Explain the underlying principles (centrifugal force, drag force) that drive these changes. What are the practical limits or trade-offs a chemical engineer must consider when optimizing inlet velocity?

3. **Design & Selection:**
   - You are designing a gas clean-up system for a new refinery process. The gas stream contains a wide range of solid particle sizes, including a significant fraction below 5 µm. Would a single cyclone separator be sufficient for achieving very high (>99%) particulate removal efficiency for all particle sizes? If not, what alternative or combined separation strategy would a chemical engineer typically propose?

6/ References

- "Air Pollution Control Engineering" (for details on gas cleaning equipment).
- "Unit Operations of Chemical Engineering" (provides an overview of cyclones).

Ministry of high Education and Scientific Research
Southern Technical University
Technological institute of Basra
Department of Chemical Industries Techniques

Learning package

In

Flotation

For

Students of First Year

By

Halah Kadhim Mohsin

Dep. Of Chemical industries Techniques

2025

1/ Overview

1/ A – Target Population: Technical institute students specializing in chemical technology, mineral processing, or environmental engineering.

1/ B – Rationale: To understand the principles and applications of froth flotation, a key method for separating fine particles based on their surface properties, especially in mineral processing.

1/ C – Central Idea: Selectively attaching air bubbles to specific solid particles in a liquid mixture, causing them to float to the surface as a foam (froth) while other particles remain in the liquid.

1/ D – Performance Objectives:

By the end of this lecture, students will be able to define froth flotation.

- To explain the role of air bubbles and surface properties in flotation.
- To identify common applications of flotation in industry.

2/ Pretest

- What happens when you mix oil and water? Do they mix?
- If you throw a small stone and a piece of wood into water, which one floats? Why?
- What is a "bubble"?

3/Lecture

1. Introduction to Flotation

Definition: Flotation is a physical separation process that selectively separates hydrophobic (water-repelling) particles from hydrophilic (water-attracting) particles in an aqueous suspension. This is achieved by introducing air bubbles into the suspension; the hydrophobic particles selectively attach to these air bubbles, become buoyant, and rise to the surface to form a froth layer, which can then be skimmed off. Hydrophilic particles remain in the bulk liquid.

Key Chemical Engineering Distinction: Unlike sedimentation or centrifugation which rely primarily on density differences, flotation exploits differences in *surface properties* of particles. This makes it particularly effective for separating very fine particles or components with densities very close to that of the liquid phase.

Importance in Chemical Engineering and Petroleum Refining: While traditionally known for mineral processing, flotation, especially its dissolved air flotation (DAF) variant, is a critical unit operation in chemical plants and refineries for:

- **Wastewater Treatment:** A primary and often essential step for removing finely dispersed oil droplets, suspended solids, and certain organic matter from industrial effluents.
- **Product Recovery:** In specific chemical processes, it can be used to recover valuable fine solid particles or even liquid droplets that are difficult to separate by other means.
- **Pollution Control:** Reducing the pollutant load (e.g., oil and grease, suspended solids, BOD/COD) in discharge streams to meet environmental regulations.

2. Principle of Operation

The core principle involves creating a stable three-phase interface (solid-liquid-gas or liquid-liquid-gas) where the gas bubbles selectively adhere to the target particles/droplets.

1. **Particle Hydrophobicity:** The target particles/droplets must be hydrophobic or rendered hydrophobic through chemical conditioning.
2. **Bubble Attachment:** Air (or another gas) is introduced into the liquid as fine bubbles. When a hydrophobic particle collides with an air bubble, the particle "prefers" to attach to the air-water interface rather than remain wetted by water. This is driven by the reduction in surface energy.
3. **Buoyancy:** The attached particle-bubble aggregate becomes sufficiently buoyant to rise through the liquid column.
4. **Froth Formation:** As these aggregates accumulate at the surface, they form a stable froth (or foam) layer, which traps the separated material.
5. **Skimming:** The froth is continuously or intermittently removed from the surface, while the clarified liquid flows out from the bottom.

The contact angle (θ) is a key concept here: a larger contact angle between the air bubble and the particle surface (measured through the liquid phase) indicates greater hydrophobicity and better attachment.

3. Key Reagents and Chemical Control (Crucial for Chemical Engineers)

The successful operation of flotation systems, especially for industrial wastewater or fine chemical separations, heavily relies on the precise dosage and interaction of chemical reagents.

1. **Collectors (Promoters):**
    - **Function:** Organic chemicals that adsorb onto the surface of the target particles, rendering them hydrophobic and enabling bubble attachment. They have a polar (hydrophilic) group that attaches to the particle surface and a non-polar (hydrophobic) hydrocarbon chain that projects into the water.

- **Examples:** Fatty acids (e.g., oleic acid) and their soaps for oxide minerals; amines for silicate minerals; xanthates for sulfide minerals. For oil/grease in DAF, the oil itself is often sufficiently hydrophobic, but sometimes specific conditioning agents are used.
- **Chemical Engineering Importance:** Proper collector selection is paramount for selectivity and efficiency. Overdosing can lead to non-selective flotation of unwanted materials, while underdosing leads to poor recovery.

2. **Frothers:**
   - **Function:** Surfactants (surface-active agents) that stabilize the air bubbles, preventing them from coalescing into larger, less effective bubbles and forming a stable froth layer that can be easily skimmed off. They lower the surface tension of water at the air-water interface.
   - **Examples:** Alcohols (e.g., methyl isobutyl carbinol - MIBC), polyglycols, pine oil.
   - **Chemical Engineering Importance:** Controls bubble size and froth characteristics. Too much frother can create excessive, stable froth that is difficult to handle.
3. **Modifiers (Regulators):**
   - **Function:** Chemicals used to adjust the surface chemistry of particles, pH of the pulp, or ionic strength to enhance selectivity (e.g., making unwanted particles more hydrophilic) or to activate desired particles.
   - **Types:**
     - **pH Modifiers:** Acids (e.g., H_2SO_4) or bases (e.g., NaOH, lime) to adjust the pulp pH, which significantly affects collector adsorption and particle surface charge.
     - **Depressants:** Make specific minerals or impurities hydrophilic, preventing them from floating (e.g., starch for clay, sodium cyanide for pyrite).

        - **Activators:** Enhance the floatability of certain minerals (e.g., copper sulfate to activate sphalerite).
    - **Chemical Engineering Importance:** Allows for fine-tuning the separation and achieving high purity, especially in complex mixtures.

4. Types of Flotation Systems and Equipment

1. **Froth Flotation (Most Common for Mineral/Chemical Solid Separation):**
    - **Mechanism:** Air is directly introduced into the agitated slurry, typically by mechanical impellers or through spargers (pneumatic cells). The impeller disperses air into fine bubbles and keeps solids suspended.
    - **Equipment:** Flotation cells (mechanical cells with impellers, or pneumatic cells that rely on gas injection).
    - **Applications:** Primarily in mineral processing (e.g., copper, lead, zinc ores). Less common in refining directly for primary product/catalyst separation, but principles can apply to niche chemical solids.
2. **Dissolved Air Flotation (DAF) (Crucial for Petroleum Refining & Wastewater Treatment):**
    - **Mechanism:** Air is dissolved into a portion of the wastewater under pressure (e.g., 5-7 atm) to achieve supersaturation. This pressurized water is then released through a pressure-reducing valve into an atmospheric flotation tank. The sudden pressure drop causes the dissolved air to come out of solution as microscopic bubbles (20-80 µm), which attach to oil droplets, suspended solids, or flocculated particles, floating them to the surface.
    - **Equipment:**
        - **Air Saturation Vessel:** Where air is dissolved into the recycle stream.

        - **Pressure Release Valve:** Key component for bubble formation.
        - **Flotation Tank:** Large tank with baffles, skimmers, and a sludge removal system.
    - **Advantages:** Highly effective for fine oil droplets and light suspended solids, creates small, uniformly sized bubbles, often produces a high-clarity effluent.
    - **Disadvantages:** Higher capital cost than gravity settlers, requires power for pumps/compressors, generates a high-water-content oily sludge.

5. Applications in Petroleum Refining and Chemical Industries (Detailed)

1. **Refinery Wastewater Treatment (Primary Application for DAF):**
    - **Oil and Grease Removal:** DAF units are extensively used after API separators (or sometimes in place of them for certain types of wastewater) to remove residual fine oil droplets and emulsified oil from refinery wastewater. These oil particles are often too fine or have densities too close to water to settle effectively by gravity.
    - **Suspended Solids Removal:** DAF is also effective in removing very fine suspended solids, including biological floc from secondary treatment effluent, improving the overall water quality.
    - **Impact:** Crucial for meeting stringent discharge limits for oil and grease, Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), and Biological Oxygen Demand (BOD), enabling compliance with environmental regulations. It also protects downstream biological treatment units from excessive oil loading.
2. **Chemical Wastewater Treatment:** Similar to refineries, DAF is used in various chemical plants for treating effluents containing oils, greases, fibers, pigments, or biological sludge.

3. **Product/By-product Recovery (Niche Applications):**
    - In some niche chemical processes, if a valuable solid by-product is produced as fine, hydrophobic particles in a dilute aqueous suspension, flotation could be considered for recovery.
    - Separation of plastics for recycling.

6. Chemical Engineering Design and Operational Considerations

- **Wastewater Characterization:** Thorough analysis of the wastewater composition (oil content, TSS, pH, temperature, presence of emulsifying agents) is critical for DAF design.
- **Chemical Dosage Optimization:** Careful selection and precise control of coagulants (e.g., aluminum sulfate, ferric chloride) and flocculants (polyelectrolytes) upstream of the DAF unit. These chemicals aggregate fine particles and oil droplets into larger, more floatable flocs. This is a critical chemical aspect.
- **Air-to-Solids Ratio (A/S Ratio):** Key design parameter for DAF, representing the mass of air applied per mass of solids/oil to be floated. Optimized based on pilot tests.
- **Recycle Ratio:** The percentage of treated effluent recycled to the air saturation vessel. Affects the amount of dissolved air.
- **Bubble Size and Distribution:** Smaller, uniformly sized bubbles are more efficient. The design of the pressure release valve and the tank hydraulics are important.
- **Hydraulics:** Ensuring proper flow distribution within the DAF tank to minimize turbulence that could break flocs.
- **Skimming Mechanism:** Design of the skimmer (e.g., chain and flight, rotating drum) for efficient removal of the froth layer.
- **Sludge Management:** The skimmed froth (DAF sludge) is typically a high-water-content, oily sludge that requires further dewatering (e.g., by decanter centrifuges or filter presses) and

disposal. This is a significant operational and environmental challenge.
- **Temperature Effects:** Higher temperatures generally decrease water viscosity, which can improve bubble generation and contact, but also increase volatility of some components.

Example Problem: DAF System Sizing for Refinery Wastewater

Problem Statement: A refinery's wastewater stream has a flow rate of 200 m3/h and contains 150 mg/L of oil and suspended solids. A pilot-scale DAF unit indicated that an effective superficial rise velocity for the floated material is 0.003 m/s when using optimal chemical conditioning and a specific air-to-solids ratio.

Calculate the required surface area of the DAF flotation tank.

Given Data:

- Wastewater flow rate (Q) = 200 m3/h
- Superficial rise velocity (vr) = 0.003 m/s
- Oil/solids concentration = 150 mg/L (This information is important for chemical dosage and A/S ratio but not directly for tank *surface area* sizing if vr is known).

Solution Steps:

1. **Convert Flow Rate to Consistent Units:** The rise velocity is in m/s, so convert the flow rate from m^3/h to m^3/s: Q=200hm3×3600 s1 h=0.05556 m3/s
2. **Determine Required Surface Area (A):** The required surface area is simply the volumetric flow rate divided by the superficial rise velocity (similar to overflow rate in sedimentation, but for rising material): A=vrQ A=0.003 m/s0.05556 m3/s A=18.52 m2

Answer: The required surface area of the DAF flotation tank is approximately **18.52 m2**. This surface area ensures that the rising oil and solids have sufficient area to surface and be removed, while allowing the clarified water to be collected from below.

4/ Posttest

- What is the main principle behind froth flotation?
- Explain the difference between a hydrophobic and a hydrophilic particle. Which one do we want to float?
- What is the role of "collectors" and "frothers" in flotation?
- Give two examples of industries where flotation is commonly used.

5/ Homework

1. **Chemical Aspects of DAF:**
    - Explain the distinct roles of **coagulants** and **flocculants** in a Dissolved Air Flotation (DAF) system used for refinery wastewater treatment. Why are these chemical additives often essential for DAF to be effective in removing oil droplets and very fine suspended solids?
    - How does adjusting the **pH** of the wastewater feed affect the performance of a DAF unit, specifically concerning the action of chemical reagents (coagulants/flocculants) and the stability of the pollutants?
2. **Operational Challenges & Optimization:**
    - A refinery's DAF unit is showing poor performance, with excessive oil and suspended solids in the effluent. What are three potential operational issues related to the **air**

dissolution system or bubble generation that a chemical engineer would investigate?
    - The DAF unit produces a large volume of oily sludge (froth) with high water content. From a chemical engineering and environmental perspective, discuss the challenges associated with managing this DAF sludge and potential next steps for its treatment.
3. **Comparative Separation:**
    - You have a refinery wastewater stream containing significant amounts of very fine clay particles (hydrophilic) and fine oil droplets (hydrophobic). Discuss why **DAF** would likely be more effective than a conventional **gravity clarifier** for removing both these types of contaminants.

6/ References

- "Mineral Processing Technology" (for detailed information on flotation in mining).
- "Unit Operations of Chemical Engineering" (provides general principles of separation).

Ministry of high Education and Scientific Research
Southern Technical University
Technological institute of Basra
Department of Chemical Industries Techniques

Learning package

In

Filtration

For

Students of First Year

By

Halah Kadhim Mohsin

Dep. Of Chemical industries Techniques

2025

1/ Overview

1/ A – Target Population: Technical institute students specializing in chemical technology, water treatment, or industrial processes.

1/ B – Rationale: To understand the fundamental principles and various types of filtration, which is a universally applied method for separating solid particles from fluids (liquids or gases).

1/ C – Central Idea: The process of separating solid particles from a fluid by passing the fluid through a porous medium that allows the fluid to pass but retains the solids.

1/ D – Performance Objectives:

- By the end of this lecture, students will be able to define filtration.
- To explain the basic mechanism of how filtration works.
- To identify the key components of a filtration system.
- To list common applications of filtration in different industries.

2/ Pretest

- What is the purpose of a sieve (منخل) in separating sand from gravel?
- When you pour water through a kitchen strainer, what stays in the strainer and what goes through?
- Why do we have air filters in cars or vacuum cleaners?

3/Lecture Content

1. Introduction to Filtration

Definition: Filtration is a mechanical or physical separation process that separates suspended solid particles from a fluid (liquid or gas) by passing the fluid through a porous medium. The filter medium (e.g., cloth, membrane, granular bed) allows the fluid (filtrate or clean gas) to pass through, while retaining the solid particles (filter cake or dust).

Importance in Chemical Engineering and Petroleum Refining: Filtration is a ubiquitous and critically important unit operation in the chemical and refining industries, often serving to:

- **Achieve High Product Purity:** Ensuring products meet strict quality specifications (e.g., clear fuels, pure pharmaceuticals, contaminant-free solvents).
- **Protect Downstream Equipment:** Preventing fouling, erosion, or blinding of sensitive equipment such as heat exchangers, pumps, catalyst beds, and nozzles.
- **Recover Valuable Solids:** Separating and recovering desired solid products (e.g., catalysts, crystalline chemicals, polymers) from process slurries.
- **Environmental Compliance:** Removing suspended solids from wastewater streams or particulates from gas emissions to meet discharge regulations.
- **Process Optimization:** Clarifying recycle streams, or preparing feedstocks for further processing steps.

2. Fundamental Principles of Filtration

1. **Mechanism of Separation:**

- **Surface Filtration (Cake Filtration):** The most common mechanism in chemical processing. Solids are deposited primarily on the surface of the filter medium, building up a "filter cake." This cake then becomes the primary filtering medium, trapping subsequent incoming solids. The filter medium itself typically only retains the initial layer of solids.
- **Deep Bed Filtration (Depth Filtration):** Solids are captured *within* the tortuous channels and pores of a relatively thick filter medium (e.g., sand filter, fibrous cartridge filter). This mechanism is common for low concentrations of fine solids where a "cake" doesn't readily form, such as in water treatment.

2. **Driving Force:** The fluid is forced through the filter medium and the accumulated filter cake by a **pressure differential** (ΔP) across the filter. This pressure can be applied via pumps (positive pressure) or by creating a vacuum on the downstream side (negative pressure).
3. **Darcy's Law and Filtration Theory (The Chemical Engineer's Toolkit):** Darcy's Law describes fluid flow through porous media and is the cornerstone of filtration design. For constant-pressure cake filtration, the rate of filtrate flow (dV/dt) can be expressed as:

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

Where:

- dV/dt: Volumetric flow rate of filtrate (m^3/s)
- A: Filter area (m^2)
- ΔP: Pressure drop across the filter (Pa)
- μ: Viscosity of the filtrate (Pa·s) - **Crucially, fluid viscosity is a major factor controlled by temperature in chemical processes.**
- α: Specific cake resistance (m/kg) - **This is a key parameter for chemical engineers.** It represents the resistance offered by a unit mass of dry filter cake per unit filter area. It is highly dependent on particle size, shape, and especially **cake compressibility**.
- W: Mass of dry filter cake accumulated on the filter (kg)
- R_m: Resistance of the filter medium (m^{-1}) - Relatively constant.

1. **Chemical Engineering Significance:**
    - This equation allows engineers to predict filtration rates, size filters, and understand how slurry properties (viscosity, particle characteristics affecting α) and operating conditions (ΔP) impact performance.
    - **Cake Compressibility:** For many chemical sludges (e.g., precipitated solids, biological sludges), the filter cake is compressible. This means its specific resistance (α) increases with increasing pressure drop (ΔP), making filtration more difficult at higher pressures. Understanding this behavior (via filtration tests) is critical.

3. Types of Filtration Processes

Filtration processes are often classified by how the pressure is applied and managed:

- **Constant Pressure Filtration:** The pressure differential is kept constant. As the cake builds up, its resistance increases, causing the filtration rate to continuously decrease over time.
- **Constant Rate Filtration:** The flow rate of filtrate is kept constant by gradually increasing the pressure differential as the cake resistance increases. This continues until a maximum allowable pressure is reached.
- **Variable Pressure/Variable Rate Filtration:** A combination, where the filter might start at constant rate and then switch to constant pressure as the resistance builds up. This is a common industrial practice.

4. Filter Media and Aids

- **Filter Media:** The porous material that separates solids from liquids. Key requirements for chemical applications include chemical compatibility (resistance to corrosion/degradation by process fluids), thermal stability, mechanical strength, and appropriate pore size.
    - **Common Types:** Woven fabrics (cotton, nylon, polypropylene), metallic meshes, porous plates (sintered metal, ceramics), membranes (for microfiltration, ultrafiltration).
- **Filter Aids:** Materials added to the slurry or applied as a pre-coat to the filter medium to improve filtration performance.
    - **Function:** They create a more permeable, rigid, and incompressible filter cake, preventing the blinding of the filter medium, improving clarity, and increasing filtration rate, especially for fine, gelatinous, or compressible solids.
    - **Examples:** Diatomaceous earth (DE), perlite, cellulose fibers, activated carbon.
    - **Chemical Engineering Importance:** Used extensively in food, beverage, pharmaceutical, and some chemical

processes where high clarity or efficient separation of difficult-to-filter slurries is needed.

5. Applications in Petroleum Refining and Chemical Industries

1. **Fuel and Lubricant Purification (Refining):**
    - **Final Product Polishing:** Critical for producing high-spec fuels (jet fuel, diesel, gasoline) free of particulates (rust, dirt, scale, small catalyst fines) that can damage engines, fuel systems, or contaminate downstream processes.
    - **Lube Oil Filtration:** Removing carbon residue, metal fines, and other impurities from lubricating oils to extend equipment life and ensure performance.
    - **Guard Filters:** Installed upstream of sensitive equipment (e.g., hydrotreating catalyst beds) to remove tramp solids that could foul or poison the catalyst.
2. **Molten Sulfur Filtration (Refining):**
    - In Sulfur Recovery Units (SRUs), elemental sulfur produced often contains entrained solids (e.g., carbon, iron sulfide). Filtration of molten sulfur (using pressure leaf filters or cartridge filters) is essential to produce high-purity sulfur for sale or further processing.
3. **Chemical Product Isolation and Purification:**
    - **Crystallization Processes:** Filtering crystalline products (e.g., salts, polymers, pharmaceuticals) from their mother liquor. Often involves washing the filter cake to remove impurities.
    - **Catalyst Recovery:** Separating solid catalysts from reaction slurries for reuse or regeneration.
    - **Clarification of Chemical Solutions:** Removing precipitated impurities or haze from liquid products (e.g., edible oils, beverages, specialty chemicals).
4. **Wastewater Treatment (Tertiary Treatment):**

    - Removing residual suspended solids from refinery or chemical plant effluents after primary and secondary treatment to meet stringent discharge limits or for water reuse applications. Deep bed filters (e.g., sand filters) are common here.
5. **Recycling and Solvent Recovery:**
    - Filtering used solvents or wash liquids to remove suspended solids before distillation or reuse, improving process economics and reducing waste.

6. Chemical Engineering Design & Operational Considerations

- **Slurry Characterization:** Detailed knowledge of particle size distribution, concentration, density, liquid viscosity, and slurry temperature is essential. Temperature control is often used to manipulate liquid viscosity and thus filtration rate.
- **Cake Compressibility:** Performing batch filtration tests (constant pressure or constant rate) to determine the specific cake resistance (α) and its relationship with pressure for compressible cakes. This dictates the optimal operating pressure.
- **Filter Medium Selection:** Choosing the correct medium based on particle retention efficiency, pressure drop, chemical compatibility, and durability.
- **Filter Cycle Optimization:** Determining the optimal balance between filtration time (cake buildup), cake washing, and solids discharge. Too long a cycle leads to very slow filtration rates.
- **Cake Washing:** Designing for effective washing to remove residual mother liquor or impurities. This involves displacement washing (passing clean liquid through the cake) and sometimes resuspension washing.
- **Cake Deliquoring/Drying:** Strategies to reduce moisture content in the filter cake (e.g., air blowing, steam blowing, mechanical compression).

- **Materials of Construction:** Selecting materials that can withstand the corrosive nature of chemical process fluids and operating temperatures/pressures.
- **Safety:** Handling flammable solvents, toxic chemicals, and operating under high pressures requires robust safety protocols, explosion-proof equipment, and proper ventilation.

Example Problem: Filtration Rate Calculation for Catalyst Slurry

Problem Statement:

A chemical engineer is tasked with evaluating a filter for separating a catalyst slurry. A batch filtration test at constant pressure ($\Delta P = 2\ \text{atm}$) on a laboratory filter with a filtration area (A) of $0.01\ \text{m}^2$ yielded the following data for the filtrate volume (V) vs. time (t):

Time (min)	Filtrate Volume (L)
0	0
1	0.5
4	1.0
9	1.5
16	2.0

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The viscosity of the filtrate (μ) is $1.0 \times 10^{-3}\ \text{Pa} \cdot \text{s}$. The filter medium resistance (R_m) can be considered negligible for this highly resistant cake.

Estimate the specific cake resistance (α) of the catalyst cake, and then predict the filtration time required to collect $5\ \text{L}$ of filtrate using the same filter at the same pressure.

Relevant Equation for Constant Pressure Filtration (integrated form, assuming $R_m \approx 0$):

$$\frac{t}{V} = \frac{\mu \alpha C}{2A^2 \Delta P} V$$

Where C is the concentration of solids in the slurry ($kg\ \text{dry solids}/m^3\ \text{filtrate}$).
This equation is in the form of $y = mx$, where $y = t/V$ and $x = V$. The slope $m = \frac{\mu \alpha C}{2A^2 \Delta P}$.

To simplify, let's assume 'C' is a constant incorporated into the slope, or better, we can use the linear relationship derived from the integrated form of Darcy's Law for constant pressure:

$\frac{dt}{dV} = \frac{\mu \alpha V}{A^2 \Delta P} + \frac{\mu R_m}{A \Delta P}$ (This is rate equation for a differential element)

Integrating for total volume V:
$t = \frac{\mu\alpha}{2A^2\Delta P}V^2 + \frac{\mu R_m}{A\Delta P}V$

Since R_m is negligible, the equation simplifies to:
$t = \frac{\mu\alpha}{2A^2\Delta P}V^2$ or $\frac{t}{V} = \frac{\mu\alpha}{2A^2\Delta P}V$

Given Data:

- $\Delta P = 2 \text{ atm} = 2 \times 101325 \text{ Pa} = 202650 \text{ Pa}$
- $A = 0.01 \text{ m}^2$
- $\mu = 1.0 \times 10^{-3} \text{ Pa} \cdot \text{s}$
- $R_m \approx 0$

Solution Steps:

1. **Convert Data to t/V vs. V:** Convert Liters to m^3 (1 L = 0.001 m^3).

Time (min)	Time (s)	Filtrate Volume (L)	Filtrate Volume (m^3)	t/V (s/m^3)
1	60	0.5	0.0005	$60/0.0005 = 120000$
4	240	1.0	0.001	$240/0.001 = 240000$
9	540	1.5	0.0015	$540/0.0015 = 360000$
16	960	2.0	0.002	$960/0.002 = 480000$

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2. **Determine the slope from the linear plot of t/V vs. V:**
   The relationship is $\frac{t}{V} = mV$.
   We can pick two points to find the slope, or better, use linear regression. Let's use two points for simplicity.

Point 1: $(V_1, (t/V)_1) = (0.0005, 120000)$
Point 2: $(V_2, (t/V)_2) = (0.002, 480000)$
Slope $m = \frac{(t/V)_2 - (t/V)_1}{V_2 - V_1} = \frac{480000 - 120000}{0.002 - 0.0005} = \frac{360000}{0.0015} = 2.4 \times 10^8 \text{ s/m}^6$

3. **Calculate α from the slope:**
   We know $m = \frac{\mu\alpha}{2A^2\Delta P}$.
   So, $\alpha = \frac{2A^2\Delta P m}{\mu}$
   $\alpha = \frac{2 \times (0.01 \text{ m}^2)^2 \times (202650 \text{ Pa}) \times (2.4 \times 10^8 \text{ s/m}^6)}{1.0 \times 10^{-3} \text{ Pa·s}}$
   $\alpha = \frac{2 \times 10^{-4} \text{ m}^4 \times 202650 \text{ Pa} \times 2.4 \times 10^8 \text{ s/m}^6}{1.0 \times 10^{-3} \text{ Pa·s}}$
   $\alpha = \frac{9.7272 \times 10^6 \text{ Pa·s·m}^{-2}}{1.0 \times 10^{-3} \text{ Pa·s}}$
   $\alpha \approx 9.727 \times 10^9 \text{ m/kg}$ (This unit is for m/kg not m^{-1} as in some conventions, if C is kg/m^3 then α is m/kg)

   *(Self-correction: The unit for α (specific cake resistance) is typically m/kg when C (solids concentration in filtrate) is in kg/m^3. Let's ensure consistency here. The simplified equation $t/V = \frac{\mu\alpha C}{2A^2\Delta P}V$ implicitly takes C into account. The common form of α is m/kg or m^{-2} sometimes). Let's use the first equation and ensure we are clear about C. Or for simplification: $t = K_p V^2 + K_i V$. With $R_m = 0$, $t = K_p V^2$. Here $K_p = \frac{\mu\alpha C}{2A^2\Delta P}$. Let's ensure C is known or calculated.

A more robust method for α requires knowing C. Let's re-evaluate the interpretation of the slope for α directly, without necessarily assuming C is factored in:
The direct integrated form for filtration where $t = \frac{\mu\alpha}{2A^2\Delta P}V^2$ is what we used ($R_m = 0$).
So, $\alpha = \frac{2A^2\Delta P t}{\mu V^2}$. Let's pick a point, e.g., $V = 0.002 \text{ m}^3$ at $t = 960$ s.
$\alpha = \frac{2 \times (0.01)^2 \times 202650 \times 960}{1.0 \times 10^{-3} \times (0.002)^2}$
$\alpha = \frac{2 \times 10^{-4} \times 202650 \times 960}{1.0 \times 10^{-3} \times 4 \times 10^{-6}}$
$\alpha = \frac{38890.8}{4 \times 10^{-9}}$
$\alpha = 9.7227 \times 10^{12} \text{ m}^{-2}$ (This would be if α is defined differently. Let's stick to the t/V plot and the slope definition.)

The interpretation of $t/V = mV$ is correct if $t = mV^2$.
So $m = \frac{\mu\alpha}{2A^2\Delta P}$.
$\alpha = \frac{2A^2\Delta P m}{\mu}$
The units of m are s/m^6. The units of the right side should be m/kg. My formula for specific cake resistance usually has a C (solids concentration in filtrate, kg/m^3).
Let's check the units: $m = s/m^6$. $A^2 = m^4$. $\Delta P = Pa = kg/(m \cdot s^2)$. $\mu = Pa \cdot s = kg/(m \cdot s)$.
$\frac{A^2\Delta P m}{\mu} = \frac{m^4 \cdot (kg/(m \cdot s^2)) \cdot (s/m^6)}{kg/(m \cdot s)} = \frac{m^3 \cdot kg/(s^2 m^6)}{kg/(m \cdot s)} = \frac{kg/(s^2 m^3)}{kg/(m \cdot s)} = \frac{1}{s^2 m^3} \cdot ms = \frac{1}{sm^2}$. This is not m/kg.

There seems to be an issue with the typical form of the equation if C (concentration) is not explicitly given or assumed.
Let's re-state the common form of the integrated constant pressure filtration equation which explicitly accounts for 'C':
$t/V = (K_p)V + (K_i)$
Where:
$K_p = \frac{\mu \alpha C}{2A^2 \Delta P}$ (Slope)
$K_i = \frac{\mu R_m}{A \Delta P}$ (Intercept)

Given $R_m \approx 0$, then $K_i \approx 0$, so $t/V = K_p V$. This confirms the linear relationship with a zero intercept.

The problem *does not provide* the concentration of solids (C) in the slurry. Without C, we cannot calculate α in m/kg. However, we *can* calculate the constant K_p.

Let's modify the problem or infer the question correctly. It asks for α, implying it's derivable. Sometimes α in m^{-2} is used if the mass of cake is not factored in explicitly, but that's less common.

Let's assume the question implicitly asks for the combination αC or just the slope K_p.

Let's assume the question is asking for K_p first, as α cannot be determined without C.

Part 1: Calculate K_p (the slope):
From step 2 above, the slope $m = K_p = 2.4 \times 10^8 \text{ s/m}^6$.

Part 2: Predict the filtration time for 5 L of filtrate:
We use the equation $t = K_p V^2$.
Desired volume $V = 5 \text{ L} = 0.005 \text{ m}^3$.
$t = (2.4 \times 10^8 \text{ s/m}^6) \times (0.005 \text{ m}^3)^2$
$t = (2.4 \times 10^8) \times (2.5 \times 10^{-5})$
$t = 6000 \text{ s}$

Convert to minutes: $t = 6000 \text{ s} / 60 \text{ s/min} = 100 \text{ min}$.

Answer:

1. The constant (slope K_p) for this filtration process is $2.4 \times 10^8 \text{ s/m}^6$. (Without knowing the solids concentration 'C', the specific cake resistance α in m/kg cannot be uniquely

determined from this data alone).

2. The filtration time required to collect $5\ \mathrm{L}$ of filtrate using the same filter at the same pressure is $100\ \mathrm{minutes}$.

This is a more chemically sound answer given the lack of 'C'. I will explicitly state this in the solution.

Homework/Practice Questions (Chemical Engineering & Petroleum Refining Focus)

1. **Filtration Mechanism and Efficiency in Refining:**
   - In the context of producing jet fuel in a refinery, why is **final filtration (polishing)** a critical step? Describe the primary filtration mechanism (surface vs. deep bed) typically employed for this application and explain why.
   - A chemical engineer notices a significant drop in filtration rate in a pressure filter used to separate a newly synthesized polymer. What are two distinct *slurry properties* (chemical engineering parameters) that could have changed to cause this, and how would you propose to test or mitigate each?
2. **Impact of Cake Compressibility:**
   - For a highly compressible filter cake commonly encountered in chemical precipitation processes, how does increasing the operating pressure (ΔP) affect the specific cake resistance (α) and, consequently, the overall filtration rate? What does this imply for optimizing filtration of such slurries?
   - In a process where a filter aid is used (e.g., diatomaceous earth), explain how it improves filtration performance based on Darcy's Law. Provide a chemical engineering application where filter aids are commonly employed.
3. **Process Integration and Optimization:**
   - Consider a reaction where a solid catalyst is suspended in a liquid, and it needs to be separated and washed before reuse. What are the key chemical engineering considerations for designing the filtration and washing steps to ensure maximum catalyst recovery and purity while minimizing solvent loss? How would the viscosity of the solvent impact your design choices?

4/ Posttest

- Define filtration and explain its main purpose.
- What are the three main components of any filtration process (what passes through, what stays behind, and what does the separation)?

- Name two ways to provide the driving force for filtration (e.g., to make the liquid go through the filter).
- Give two industrial examples where filtration is critically important.

5/ Homework

- Describe a filtration process you encounter in your daily life (other than making coffee) and identify the filter medium, filtrate, and filter cake.
- Explain why a filter medium should have pores smaller than the particles you want to remove.

6/ References

- "Unit Operations of Chemical Engineering" by McCabe, Smith, and Harriott (or similar standard textbook).
- "Water Treatment: Principles and Design" (for specific applications in water).

Ministry of high Education and Scientific Research
Southern Technical University
Technological institute of Basra
Department of Chemical Industries Techniques

Learning package

In

Filtration equipment

For

Students of First Year

By

Halah Kadhim Mohsin

Dep. Of Chemical industries Techniques

2025

1/ Overview

1/ A – Target Population: Technical institute students specializing in chemical technology, water treatment, or industrial process operations.

1/ B – Rationale: To introduce students to the common types of filtration equipment used in various industries, understanding their design, operation, and suitable applications.

1/ C – Central Idea: Exploring different machines and systems designed to efficiently separate solids from fluids through a filter medium, considering factors like continuous vs. batch operation and the nature of the solid and fluid.

1/ D – Performance Objectives:

- By the end of this lecture, students will be able to distinguish between common types of filtration equipment.
- To describe the basic operation of at least two major types of industrial filters.
- To understand factors that influence the selection of appropriate filtration equipment for a given task.

2/ Pretest

- Name one difference between filtering coffee and filtering water for a whole city.
- What is a "filter cloth" made of?
- Why would a factory need to filter its exhaust gases before releasing them into the air?

3/Lecture Content

1. Introduction to Filtration Equipment

Building on the principles of filtration discussed previously, this lecture focuses on the diverse array of equipment used in industrial settings. The selection of appropriate filtration equipment is a critical decision for chemical engineers, heavily influenced by the specific characteristics of the slurry (solid-liquid mixture), the desired separation efficiency (filtrate clarity and cake dryness), process capacity, and economic considerations.

Filtration equipment can be broadly classified based on:

- **Operating Mode:** Batch (intermittent operation for cake removal) or Continuous (continuous cake formation and discharge).
- **Driving Force:** Pressure filtration (positive pressure applied) or Vacuum filtration (negative pressure on the filtrate side).
- **Purpose:** Cake filters (primary goal is to recover/dewater solids) or Clarifying filters (primary goal is to produce a clear liquid).

2. Types of Filtration Equipment and Applications

Here, we will explore common types of filtration equipment, highlighting their mechanisms, advantages, disadvantages, and crucial applications within petroleum refineries and the broader chemical industry.

2.1. Batch Pressure Filters (Cake Filters)

These filters operate under positive pressure and accumulate a filter cake, requiring periodic shutdown for cake removal. They are excellent for achieving high clarity and dry cakes.

1. **Plate-and-Frame Filter Press:**
    - **Mechanism:** Consists of a series of alternating plates and frames covered with filter cloth. Slurry is pumped into the frames, and filtrate passes through the cloth and plates, while solids are retained in the frames.
    - **Advantages:** Simple design, relatively low capital cost, high surface area in a compact footprint, versatile for various slurries, good cake washing capability.
    - **Disadvantages:** Batch operation (requires downtime for cake discharge), often labor-intensive for manual cake removal, open discharge can expose operators to hazardous materials.
    - **Refining/Chemical Applications:**
        - **Batch purification of specialty chemicals, dyes, and pigments.**
        - **Small-scale catalyst recovery and washing in batch reaction processes.**
        - **Dewatering of viscous or difficult-to-filter sludges in waste treatment (e.g., oily sludges that might not suit other continuous filters).**
        - General chemical solid-liquid separation where high purity is required in batch operations.
2. **Recessed Plate Filter Press (Chamber Filter Press):**
    - **Mechanism:** Similar to plate-and-frame, but the plates themselves have recessed faces, eliminating the need for separate frames. The recesses form chambers for cake accumulation. Can be highly automated for cake discharge (e.g., by plate shifting).
    - **Advantages:** More robust construction, higher pressure capabilities, often automated features (plate shifting, cake squeezing, washing, air blowing), produces drier cake, reduced labor.
    - **Disadvantages:** Still batch operation, higher capital cost than plate-and-frame.

- **Refining/Chemical Applications: Widely used for dewatering various refinery wastewater treatment sludges (e.g., DAF sludge, biological sludge from activated sludge plants, oily sludges)**. Also used for large-volume batch chemical slurries, catalyst slurries, and high-value product separations where cake dryness is critical.

3. **Leaf Filters (Pressure Leaf Filters - Vertical and Horizontal):**
    - **Mechanism:** Consist of multiple filter leaves (frames covered with filter cloth or mesh) enclosed within a pressure vessel. Slurry is pumped in, and filtrate exits the leaves. Cake accumulates on the leaf surfaces. Cake discharge is typically achieved by backwashing (slurry/filtrate), vibrating, or gravity dumping after opening the vessel. Often operated with a filter aid pre-coat.
    - **Advantages:** Fully enclosed (excellent for volatile, toxic, or flammable liquids common in refineries), high surface area in a compact vessel, good for fine solids, can handle high operating pressures, allows for efficient cake washing.
    - **Disadvantages:** Batch operation, typically requires a filter aid pre-coat for optimal performance, can be sensitive to very high solids loading.
    - **Refining/Chemical Applications: Critical for filtering molten sulfur in Sulfur Recovery Units (SRUs)** to remove entrained solids (e.g., carbon, iron sulfide) and meet purity specifications. Also used for polishing edible oils, clarification of chemical intermediates, catalyst recovery (especially where solvent washing is crucial).

2.2. Clarifying Filters (Deep Bed Filters)

These filters typically operate by trapping particles within a bed of granular media. They are used for low solids concentrations to achieve high clarity.

1. **Cartridge Filters:**
    - **Mechanism:** Consist of disposable or reusable cartridges made of various materials (e.g., pleated paper, wound string, melt-blown polymer fibers) housed within a pressure vessel. They primarily function as depth filters or surface filters depending on design.
    - **Advantages:** Simple, compact, easy to replace, low maintenance, effective for very fine particle removal and low solids concentrations, available with "absolute" filtration ratings (guaranteeing removal of particles above a certain size).
    - **Disadvantages:** High running costs if disposable, short life with high solids loading, cannot handle filter cake.
    - **Refining/Chemical Applications: Widely used as guard filters** to protect downstream pumps, heat exchangers, sensitive catalyst beds (e.g., pre-hydrotreater filters to prevent catalyst fouling/poisoning). Also critical for **final polishing of high-purity fuels (jet fuel, diesel, gasoline)** and lubricating oils to meet stringent cleanliness standards. Used for polishing small-scale process streams and solvents.
2. **Sand Filters (Multi-Media Filters):**
    - **Mechanism:** Consist of a bed of granular media (typically sand, anthracite, gravel) through which water flows, trapping suspended solids within the bed. Regularly backwashed to remove accumulated solids.
    - **Advantages:** Robust, simple, high capacity for water treatment, low operating cost.

- **Disadvantages:** Only for dilute suspensions, not for cake formation, backwash requires water.
- **Refining/Chemical Applications: Tertiary treatment of refinery wastewater** for removal of residual suspended solids, often after DAF or biological treatment, to produce high-quality effluent for discharge or reuse (e.g., cooling tower makeup water).

2.3. Continuous Filters

These filters are designed for continuous operation, with continuous cake formation and discharge.

1. **Rotary Vacuum Drum Filter (RVDF):**
   - **Mechanism:** A cylindrical drum, partially submerged in a slurry tank, rotates slowly. The drum surface is covered with a filter cloth. Vacuum is applied internally, drawing filtrate through the cloth and forming a cake on the drum surface. As the drum rotates, the cake can be washed, dewatered, and then scraped off or discharged by other means (e.g., string discharge).
   - **Advantages:** Continuous operation, high capacity for large volumes of slurry, suitable for moderately fast-filtering and non-sticky slurries, allows for efficient cake washing and dewatering.
   - **Disadvantages:** Vacuum limits pressure differential (cannot achieve very dry cakes compared to pressure filters), capital intensive, requires a complex vacuum system, open design can be an issue for hazardous slurries.
   - **Refining/Chemical Applications: Dewatering of large volumes of relatively coarse, granular sludges**, such as some catalyst slurries (if not too fine/sticky), activated carbon slurries, large volume municipal or industrial

wastewater sludges. Often used for gypsum dewatering in desulfurization units.

2. **Belt Filters (Continuous Belt Filter Press):**
    - **Mechanism:** Slurry is fed onto a moving endless belt (filter cloth). Filtrate drains through the belt by gravity, often aided by vacuum boxes. The cake is then passed through a series of rollers for mechanical dewatering (squeezing).
    - **Advantages:** Continuous operation, high capacity, excellent for dewatering compressible and sticky sludges, effective cake washing, low energy consumption for dewatering.
    - **Disadvantages:** Relatively large footprint, open design (potential for odor/emissions), can be complex mechanically.
    - **Refining/Chemical Applications: Large-scale dewatering of refinery wastewater sludges, especially biological sludges from activated sludge units and DAF sludges**, mining slurries, and various industrial waste slurries.

2.4. Specialized Filters

1. **Nutsche Filters (Agitated Nutsche Filter-Dryers - ANFD):**
    - **Mechanism:** A batch filter comprising a cylindrical vessel with a perforated bottom supporting a filter medium. It's fully enclosed and often includes an agitator that can perform multiple functions: mixing, cake smoothing, cake discharge. Can operate under pressure or vacuum, and often has heating/cooling jackets for drying.
    - **Advantages:** Highly versatile (filtration, washing, re-slurrying, drying in one unit), fully enclosed (excellent for hazardous, toxic, or high-value products, minimizing

exposure and product loss), minimal handling of wet cake.
    - **Disadvantages:** Batch operation, high capital cost, smaller capacity per unit, complex control system.
    - **Refining/Chemical Applications:** Primarily used in **pharmaceuticals, specialty chemicals, and catalyst preparation processes** where product purity, containment, solvent recovery, and multi-step processing in a single vessel are critical.
2. **Membrane Filters (Microfiltration, Ultrafiltration, Nanofiltration, Reverse Osmosis):**
    - **Mechanism:** Pressure-driven separation through semi-permeable membranes with extremely fine pores (from 0.1 µm for microfiltration down to <1 nm for RO). Separation is based on size exclusion and sometimes chemical affinity.
    - **Advantages:** Very high separation efficiency (can remove colloids, macromolecules, ions), compact modules, potential for continuous operation.
    - **Disadvantages:** High capital cost, membrane fouling (requires frequent cleaning), sensitive to suspended solids (requires pre-filtration), high energy consumption for RO (due to high pressures).
    - **Refining/Chemical Applications: Advanced refinery wastewater treatment (for water reuse, produced water treatment, achieving zero liquid discharge)**, purification of specific chemical products, solvent recovery, specialized catalyst recovery/separation (e.g., for homogeneous catalysts where molecular separation is needed).

3. Chemical Engineering Selection Criteria for Filtration Equipment

Selecting the optimal filtration equipment requires a systematic approach considering several key factors:

1. **Slurry Characteristics:**
    - **Solids Concentration:** High solids favor continuous cake filters (RVDF, Belt), low solids favor clarifying filters (cartridge, sand) or membrane filtration.
    - **Particle Size and Distribution:** Dictates the required filter medium pore size. Very fine particles might need pressure leaf, cartridge, or membrane filters.
    - **Particle Shape and Compressibility:** Highly compressible cakes are difficult for constant pressure filters; might favor specific filter presses or require filter aids.
    - **Corrosivity and Temperature:** Influences materials of construction (stainless steel, exotic alloys) and whether an enclosed system is required.
    - **Viscosity:** High liquid viscosity reduces filtration rate; pre-heating might be necessary.
2. **Separation Goal:**
    - **Filtrate Clarity:** How pure must the liquid be? (High clarity from cartridge, membrane, pressure leaf).
    - **Cake Purity/Washing:** Is the cake a valuable product that needs washing? (Filter presses, RVDF, Nutsche).
    - **Cake Dryness:** How low must the moisture content of the cake be? (Filter presses, especially recessed plate with squeezing, Nutsche).
3. **Process Requirements:**
    - **Capacity:** Required flow rate of slurry and solids loading.
    - **Operating Mode:** Batch or continuous operation.

- **Automation Level:** Manual vs. highly automated systems.
- **Safety:** Handling flammable, toxic, or hazardous materials dictates enclosed systems.

4. **Economic Factors:**
   - **Capital Cost:** Initial purchase and installation.
   - **Operating Costs:** Energy consumption (pumps, vacuum), labor, filter media replacement, chemical consumption (for cleaning or filter aids), maintenance.
   - **Return on Investment:** Value of recovered product vs. cost of filtration.

Example Problem: Filtration Equipment Selection in a Refinery

Problem Statement: A large petroleum refinery generates a significant volume of oily wastewater from its process units. After preliminary gravity separation (API separator) and DAF (Dissolved Air Flotation), the wastewater still contains a high concentration of very fine, biological floc (from an activated sludge unit) and some residual oil droplets. The refinery needs to dewater this sludge to reduce its volume by at least 80% before disposal. The sludge is somewhat compressible, sticky, and has a relatively high water content. The process must be continuous to handle the large wastewater flow.

Recommend the most suitable type of filtration equipment for dewatering this specific sludge, and justify your choice based on the sludge characteristics and process requirements. Also, mention one key operational challenge for this chosen equipment.

Solution Approach:

1. Analyze Sludge Characteristics and Requirements:

- Source: Biological floc and residual oil from wastewater treatment.
- Nature: Very fine, biological floc; somewhat compressible, sticky; high water content.
- Goal: Dewater to reduce volume by 80% (implies achieving a high solids concentration/low moisture content in the cake).
- Operation: Continuous, large volume.

2. Evaluate Filtration Equipment Options:
   - Plate-and-Frame/Recessed Plate Filter Press: Excellent for dewatering, good cake dryness, can handle compressible/sticky. But, they are batch operations, not suitable for continuous, large-volume dewatering.
   - Leaf Filters: Good for fine solids, enclosed, but primarily for lower solids concentration clarification and batch operation. Not ideal for dewatering high-volume sludges.
   - Cartridge Filters: For very low solids clarification only, not for dewatering sludges.
   - Rotary Vacuum Drum Filter (RVDF): Continuous. Can handle large volumes. However, vacuum limits dewatering effectiveness for highly compressible/sticky sludges. May struggle to achieve 80% volume reduction if the cake retains too much water.
   - Belt Filter Press: Continuous, designed for high-volume dewatering of sludges, uses mechanical compression for good dewatering (suited for compressible/sticky sludges), relatively high solids capture.
   - Nutsche Filter: Excellent for dewatering and drying but strictly batch and typically for smaller, high-value batches due to high cost. Not for large, continuous wastewater sludge.
   - Membrane Filters: Primarily for water purification (filtrate) and extremely fine separations, not for high-volume dewatering of concentrated sludges.

3. Recommendation and Justification:

   The most suitable type of filtration equipment for dewatering this refinery wastewater sludge is a Belt Filter Press.

   Justification:

   - Continuous Operation: It is designed for continuous processing of large volumes of sludge, directly meeting the refinery's operational requirement.
   - Sludge Characteristics: Belt filter presses are particularly effective for dewatering compressible, sticky, and high-water-content sludges, such as biological floc and oily wastewater sludges. The mechanical compression applied by the rollers efficiently squeezes out water.
   - Volume Reduction: They are capable of achieving high volume reduction (dewatering efficiency) for these types of sludges, likely meeting the 80% target.
   - Cost-Effectiveness: For large volumes of sludge, they offer a good balance of capital and operating costs compared to other continuous dewatering options like large centrifuges (decanters), although decanters are also widely used.

4. Key Operational Challenge:

   A key operational challenge for a belt filter press is optimizing the chemical conditioning (flocculant dosage and mixing) of the sludge upstream of the filter. Biological floc and oily sludges often require precise flocculant addition to create strong, permeable flocs that can be effectively dewatered without blinding the belt or being washed out with the filtrate. Inadequate flocculation leads to poor dewatering, high solids in the filtrate, and operational issues.

4/ Posttest

- Briefly describe how a Plate and Frame Filter Press works.
- What is the main advantage of a continuous filter (like a Rotary Vacuum Filter) over a batch filter?
- Explain the primary function of a Bag Filter.
- Name two factors that an engineer would consider when choosing a type of filtration equipment.

5/ Homework

1. Selection for Specific Refinery Streams:
    - A refinery needs to install a new filtration system to ensure the final purity of its jet fuel product, removing any particulate matter down to a few micrometers before shipment. Which specific type of filter would a chemical engineer recommend for this task, and why is this choice superior to a plate-and-frame filter press or a rotary vacuum drum filter for this particular application?
    - In a molten sulfur recovery unit (SRU), solid impurities need to be removed from the liquid sulfur product. Which filtration equipment type is commonly used for this, and what advantages does it offer given the high temperature and potentially corrosive nature of molten sulfur?
2. Operational Considerations and Troubleshooting:
    - You are operating a recessed plate filter press that is used to dewater a catalyst slurry in a batch chemical process. You notice that the filtration cycle time is increasing significantly over several batches, and the cake dryness is decreasing. As a chemical engineer, list three potential reasons for this operational problem related to the filter or slurry, and suggest a possible solution for each.

    - Why would a chemical engineer choose to use a Nutsche filter-dryer for the production of a highly valuable, hazardous, and temperature-sensitive specialty chemical, even though it is a batch operation with a high capital cost? What key benefits does it offer in this context?
3. Comparing Technologies:
    - Compare and contrast the primary advantages and disadvantages of using a Rotary Vacuum Drum Filter (RVDF) versus a Centrifuge (e.g., Decanter Centrifuge) for dewatering a large volume of industrial wastewater sludge. Discuss their suitability based on sludge characteristics (compressibility, fine particles) and continuous operation requirements.

6/ References

- "Chemical Process Equipment: Selection and Design" by James R. Couper, et al.
- "Unit Operations of Chemical Engineering" by McCabe, Smith, and Harriott.
- Industrial equipment manufacturer's brochures and websites.

Ministry of high Education and Scientific Research
Southern Technical University
Technological institute of Basra
Department of Chemical Industries Techniques

Learning package

In

Size reduction

For

Students of First Year

By

Halah Kadhim Mohsin

Dep. Of Chemical industries Techniques

2025

1/ Overview

1/ A – Target Population: Technical institute students specializing in chemical technology, mineral processing, food processing, or any industry involving solid materials.

1/ B – Rationale: To understand the principles and equipment used for reducing the size of solid materials, which is a crucial operation in many manufacturing processes for various purposes.

1/ C – Central Idea: Applying mechanical forces (compression, impact, attrition, cutting) to break down larger solid particles into smaller ones, increasing surface area and facilitating subsequent operations.

1/ D – Performance Objectives:

- By the end of this lecture, students will be able to define size reduction.
- To explain the main reasons for performing size reduction in industry.
- To identify the primary mechanisms (forces) used in size reduction equipment.
- To list common types of size reduction machines.

2/ Pretest

- If you want to dissolve sugar quickly in your tea, should you use sugar cubes or granulated sugar? Why?
- What happens if you hit a rock with a hammer?
- Why do farmers grind animal feed?

Lecture Content

1. Introduction to Size Reduction

Definition: Size reduction, also known as comminution or grinding, is a mechanical operation that involves breaking solid materials into smaller particles. This process is fundamental across many industries, including chemical processing, pharmaceuticals, food, and mining.

Primary Goals in Chemical Engineering and Petroleum Refining: Size reduction is performed for various strategic reasons, often to:

- **Increase Surface Area:** Smaller particles have a much larger surface area-to-volume ratio. This is crucial for:
  - **Reaction Kinetics:** Accelerating chemical reactions (e.g., catalysis, combustion).
  - **Dissolution Rates:** Speeding up the dissolving of solids.
  - **Mass and Heat Transfer:** Improving rates of drying, extraction, or adsorption.
- **Improve Material Handling:** Facilitating easier transport (e.g., pneumatic conveying), mixing, or packaging.
- **Achieve Desired Particle Size Distribution (PSD):** Meeting specific product quality specifications (e.g., pigments, pharmaceuticals, specific catalyst grades).
- **Liberation of Valuable Components:** Separating valuable constituents from a composite material (e.g., in mineral processing, though less direct in typical refinery operations).
- **Waste Treatment:** Preparing solid waste for easier disposal or further processing.

2. Mechanisms of Size Reduction (Forces Involved)

Size reduction equipment applies various mechanical forces to achieve breakage:

1. **Compression:** Crushing materials by applying stress between two surfaces, often used for brittle materials and coarse reduction. (e.g., Jaw crushers, Roll crushers).
2. **Impact:** Applying sudden, forceful blows to the material, either by hammers, beaters, or by particle-to-particle collision. Effective for brittle and fibrous materials. (e.g., Hammer mills, Ball mills).
3. **Attrition (Shear/Rubbing):** Grinding or rubbing particles against each other or against a stationary surface, often used for fine grinding and soft materials. (e.g., Ball mills, Fluid energy mills).
4. **Cutting:** Slicing or shearing for specific, uniform particle shapes. (e.g., Granulators, Dicing machines).

3. Laws of Size Reduction (Energy Requirements)

Estimating the energy required for size reduction is critical for equipment selection, sizing, and operational cost analysis. Empirical laws relate energy consumption to the degree of size reduction:

1. **Kick's Law (for Coarse Crushing):** States that the energy required is proportional to the reduction ratio (change in particle size). Applies best to large particles where breakage occurs through crack propagation.

$$E \propto \ln(D_1/D_2)$$

Where E is energy, D_1 is initial size, D_2 is final size.

2. **Rittinger's Law (for Fine Grinding):** States that the energy required is proportional to the new surface area created. Applies best to fine particles where breaking involves overcoming surface forces.

$$E \propto (1/D_2 - 1/D_1)$$

3. **Bond's Law (Most Widely Used in Industry - for Intermediate Grinding):** An empirical law that bridges Kick's and Rittinger's, stating that the energy input is inversely proportional to the square root of the product particle size (D_P). It is often used for a wide range of grinding operations.

$$E = W_i \left(\frac{1}{\sqrt{D_2}} - \frac{1}{\sqrt{D_1}} \right)$$

1. Where Wi is the **Bond Work Index**, a material-specific property (energy required to reduce a unit mass of material from infinite size to 100 micrometers). **Chemical Engineering Significance:** The Bond Work Index is invaluable for predicting power consumption in industrial grinding mills and for comparing the grindability of different materials. It's determined experimentally for each material.

4. Classification of Size Reduction Equipment

Equipment is typically categorized by the size of particles they process (coarse to ultrafine).

4.1. Crushers (for Coarse Reduction, typically > 1 inch to 1/4 inch)

1. **Jaw Crusher:**
   - **Mechanism:** Materials are crushed between a stationary jaw and a movable jaw that reciprocates.
   - **Advantages:** Robust, handles very large feed sizes, high reduction ratios, good for hard, abrasive materials.

- **Disadvantages:** Batch action (intermittent), produces a non-uniform product, high noise.
- **Refining/Chemical Applications:** Used as a primary crusher for large, lumpy solid waste (e.g., breaking up spent catalyst lumps, large coke chunks from delayed coking units to make them manageable for transport or further processing like calcination).

2. **Gyratory Crusher:**
   - **Mechanism:** A crushing head rotates eccentrically within a stationary conical shell, providing continuous crushing action around the entire circumference.
   - **Advantages:** Higher capacity than jaw crushers for similar sizes, continuous operation, more uniform product than jaw crushers.
   - **Disadvantages:** Larger footprint, more complex than jaw crushers.
   - **Refining/Chemical Applications:** Similar to jaw crushers but for very high throughputs in large-scale plants handling bulk solids.
3. **Roll Crusher (Smooth or Toothed):**
   - **Mechanism:** Material is crushed between two rotating rolls.
   - **Advantages:** Good control over product size, produces fewer fines than impact crushers, less dust, lower power consumption for specific applications.
   - **Disadvantages:** Limited reduction ratio per pass, can be sensitive to sticky materials.
   - **Refining/Chemical Applications:** Crushing brittle materials like limestone for desulfurization units, preparing feed for finer grinding.

4.2. Grinders/Mills (for Intermediate to Fine Reduction, typically 1/4 inch down to 10-50 microns)

1. **Hammer Mill:**

- **Mechanism:** A rotor fitted with multiple free-swinging or fixed hammers rotates at high speed within a chamber. Material is broken by impact with the hammers and attrition against grinding plates or screens.
- **Advantages:** Versatile, high throughput, relatively simple design, can handle a wide range of materials (brittle, fibrous).
- **Disadvantages:** Produces a wide particle size distribution (many fines), can be dusty, susceptible to damage from tramp metal.
- **Refining/Chemical Applications: Pulverizing coal for boilers (in refinery power plants)**, grinding various chemical additives, breaking up agglomerated or friable solid wastes, size reduction of some catalyst precursors.

2. **Ball Mill / Rod Mill:**
   - **Mechanism:** A rotating cylindrical shell partially filled with grinding media (steel balls for ball mills, steel rods for rod mills). Material is ground by impact (cascading/cataracting media) and attrition (rubbing action of media). Can operate wet or dry.
   - **Advantages:** Can achieve very fine grinding (down to a few microns), handles abrasive materials, continuous operation, high capacity.
   - **Disadvantages:** High energy consumption, significant noise, grinding media wear (requires replacement), can generate heat.
   - **Refining/Chemical Applications: Crucial for catalyst manufacturing (e.g., grinding catalyst supports like alumina, silica, or zeolites to desired particle sizes for fluidization or specific surface area for catalytic activity)**. Also used in grinding mineral ores for chemical extraction, and pulverizing pigments.

4.3. Ultrafine Grinders (Micronizers, typically < 10 microns)

1. **Fluid Energy Mill (Jet Mill):**
    - **Mechanism:** Material is introduced into a grinding chamber where it is subjected to high-velocity jets of compressed air, steam, or inert gas. Particles collide with each other at very high speeds, leading to impact and attrition. No moving parts in the grinding zone.
    - **Advantages:** Produces extremely fine particles (sub-micron range), no attrition between grinding media and product (high purity), minimal heat generation (good for heat-sensitive materials), sterile operation possible.
    - **Disadvantages:** Very high energy consumption (for compressed gas), limited capacity, not suitable for very abrasive materials (erosion of internal surfaces), difficult to handle sticky materials.
    - **Refining/Chemical Applications: Ultrafine grinding of specialized catalysts for advanced processes (e.g., to improve dispersion or activity)**, pigments, pharmaceuticals, and other high-value powders where micron or sub-micron size is critical.

5. Auxiliary Equipment for Size Reduction Systems

- **Classifiers (Screens, Air Classifiers):** Essential for controlling the final particle size distribution. They separate the undersized (finished product) from the oversized particles, which are then recycled back to the mill for further grinding. This significantly improves grinding efficiency and controls product quality.
- **Feeders:** Ensure a consistent and controlled flow of material into the mill.
- **Dust Collection Systems:** Crucial for environmental control (preventing particulate emissions), product recovery

(collecting fine product dust), and safety (preventing dust explosions for combustible materials).

6. Chemical Engineering Design & Operational Considerations

- **Desired Particle Size Distribution (PSD):** The most important factor. The equipment choice directly depends on the target PSD and acceptable variations.
- **Energy Consumption:** Size reduction is highly energy-intensive. Bond's Law helps estimate power requirements. Optimizing operational parameters (feed rate, mill speed, grinding media load) can minimize energy costs.
- **Material Properties:**
  - **Hardness & Toughness:** Determines resistance to breakage and dictates mill type (e.g., hard materials need crushers/ball mills).
  - **Abrasiveness:** Causes wear on mill components and grinding media, leading to high maintenance costs and potential for product contamination.
  - **Moisture Content & Stickiness:** Can cause caking, blinding of screens, and difficulty in conveying, impacting efficiency.
  - **Friability:** How easily a material shatters.
- **Heat Generation:** Mechanical energy converted to heat during grinding can be significant. Cooling systems (e.g., water-cooled jackets, inert gas purging) may be required for heat-sensitive materials (e.g., certain polymers, catalysts).
- **Dust Control & Safety:** Many finely divided solids are combustible or explosive (e.g., pulverized coal, polymer powders, some organic chemicals). **Explosion prevention (e.g., inert gas blanketing with nitrogen or CO2, explosion venting, dust collection with explosion protection)** and health hazard mitigation (respirators, ventilation) are paramount.

- **Wear and Maintenance:** Abrasion is a major issue. Selecting wear-resistant materials for mill liners and grinding media is crucial to extend equipment life and minimize downtime.
- **Environmental Impact:** Noise pollution and dust emissions are significant concerns.
- **Economic Evaluation:** Balancing high capital costs for grinding equipment with significant operating costs (energy, wear parts, maintenance).

7. Specific Relevance to Petroleum Refining and Petrochemicals

- **Catalyst Manufacturing/Preparation:** This is a major application. Refineries and chemical companies often manufacture or prepare their own catalysts. Size reduction is vital for:
    - **Fluid Catalytic Cracking (FCC) Catalysts:** Grinding catalyst raw materials and the finished catalyst to the precise micron-sized range required for optimal fluidization properties in the FCC reactor and regenerator.
    - **Supported Catalysts:** Grinding support materials (e.g., alumina, silica) before impregnation, or grinding the final catalyst to expose active sites and control diffusion in fixed-bed or slurry reactors.
- **Coke Handling in Delayed Coking:** Crushing large, irregularly shaped coke lumps formed in delayed coker drums into smaller, manageable sizes for transportation, storage, or further processing (e.g., calcination for anode coke production).
- **Coal Pulverization:** For refinery power plants that use pulverized coal-fired boilers to generate steam and electricity.
- **Additives and Fillers:** Grinding various solid additives, fillers, or extenders used in petrochemical products (e.g., polymers, specialty chemicals) to achieve desired dispersion and properties.

- **Solid Waste Processing:** Size reduction of certain solid wastes for easier handling or subsequent treatment.

Example Problem: Bond Work Index for Catalyst Grinding

Problem Statement:
A chemical plant manufactures a new solid catalyst. Lab tests show that grinding this catalyst from a feed size of $D_1 = 800\ \mu\text{m}$ to a product size of $D_2 = 100\ \mu\text{m}$ in a ball mill requires $8.5\ \text{kWh/ton}$ of energy.

Calculate the **Bond Work Index (W_i)** for this catalyst material.
Then, predict the energy required (in kWh/ton) to grind the same catalyst from $D_1 = 800\ \mu\text{m}$ to a finer product size of $D_2 = 25\ \mu\text{m}$.

Bond's Law Equation:

$$E = W_i \left(\frac{1}{\sqrt{D_2}} - \frac{1}{\sqrt{D_1}} \right)$$

Where E is energy (kWh/ton), W_i is Bond Work Index (kWh/ton), D_1 and D_2 are in µm.

Given Data (Part 1):

- $D_1 = 800\ \mu\text{m}$
- $D_2 = 100\ \mu\text{m}$
- $E = 8.5\ \text{kWh/ton}$

Solution Steps:

Part 1: Calculate the Bond Work Index (W_i)

1. Rearrange Bond's Law to solve for W_i:

$$W_i = \frac{E}{\left(\frac{1}{\sqrt{D_2}} - \frac{1}{\sqrt{D_1}}\right)}$$

2. Substitute the given values:

$$W_i = \frac{8.5\ \text{kWh/ton}}{\left(\frac{1}{\sqrt{100\ \mu\text{m}}} - \frac{1}{\sqrt{800\ \mu\text{m}}}\right)}$$

3. Calculate the terms in the denominator:
   - $\frac{1}{\sqrt{100}} = \frac{1}{10} = 0.1\ \mu\text{m}^{-0.5}$

- $\frac{1}{\sqrt{800}} = \frac{1}{28.284} \approx 0.0354\ \mu\text{m}^{-0.5}$
- Denominator $= 0.1 - 0.0354 = 0.0646\ \mu\text{m}^{-0.5}$

4. Calculate W_i:

$$W_i = \frac{8.5\ \text{kWh/ton}}{0.0646\ \mu\text{m}^{-0.5}}$$

$$W_i \approx 131.58\ \text{kWh/ton}$$

Part 2: Predict Energy for Finer Grinding ($D_2 = 25\ \mu\text{m}$)

1. Use the calculated W_i and the new D_2 in Bond's Law:
   - $W_i = 131.58\ \text{kWh/ton}$
   - $D_1 = 800\ \mu\text{m}$
   - $D_2 = 25\ \mu\text{m}$
2. Calculate the terms in the parenthesis:
   - $\frac{1}{\sqrt{25}} = \frac{1}{5} = 0.2\ \mu\text{m}^{-0.5}$
   - $\frac{1}{\sqrt{800}} \approx 0.0354\ \mu\text{m}^{-0.5}$
   - Parenthesis $= 0.2 - 0.0354 = 0.1646\ \mu\text{m}^{-0.5}$
3. Calculate the required energy (E):

$$E = 131.58\ \text{kWh/ton} \times 0.1646\ \mu\text{m}^{-0.5}$$

$$E \approx 21.65\ \text{kWh/ton}$$

Answer:

1. The Bond Work Index (W_i) for this catalyst material is approximately $131.58\ \text{kWh/ton}$.
2. The energy required to grind the same catalyst from $800\ \mu\text{m}$ to $25\ \mu\text{m}$ is approximately $21.65\ \text{kWh/ton}$. (This demonstrates that grinding to finer sizes requires significantly more energy).

4/ Posttest

- Define size reduction and explain two main reasons why it's performed in industry.
- Name two different forces used by size reduction equipment to break materials.
- Briefly describe how a Jaw Crusher works.
- What type of size reduction equipment would you use to produce a very fine powder for paint?

5/ Homework

1. **Catalyst Particle Size Control:**
    - In Fluid Catalytic Cracking (FCC) units, why is it absolutely critical to control the particle size distribution of the FCC catalyst powder? Discuss how the chosen size reduction equipment (e.g., ball mills, fluid energy mills) helps achieve this, and the consequences of having too many fine particles or too many coarse particles in the catalyst inventory.
2. **Energy and Economic Considerations:**
    - A refinery is considering upgrading its power plant to use pulverized coal instead of fuel oil. Discuss the chemical engineering considerations related to the size reduction of coal for this purpose. What are the major operational costs associated with coal pulverization, and how would you use the concept of Bond Work Index to evaluate different coal sources?
3. **Safety and Environmental Impact:**

- Many size reduction operations in chemical plants handle powders that pose explosion hazards (e.g., polymer powders, some organic intermediates). Describe the primary safety concerns associated with these operations and outline at least three engineering control measures that a chemical engineer would implement to mitigate these risks.
- Beyond explosion hazards, what other significant environmental concerns are associated with industrial size reduction processes, and how are these typically addressed?

6/ References

- "Unit Operations of Chemical Engineering" by McCabe, Smith, and Harriott (or similar standard textbook).
- "Chemical Engineering Design" by Gavin Towler and Ray Sinnott.
- Manufacturers' catalogs for crushing and grinding equipment.

Ministry of high Education and Scientific Research
Southern Technical University
Technological institute of Basra
Department of Chemical Industries Techniques

Learning package

In

Size reduction equipment

For

Students of First Year

By

Halah Kadhim Mohsin

Dep. Of Chemical industries Techniques

2025

1/ Overview

1/ A – Target Population: Technical institute students specializing in chemical technology, mineral processing, food processing, or related industrial fields.

1/ B – Rationale: To provide a more in-depth understanding of the design, working principles, and specific applications of key industrial size reduction equipment, enabling students to differentiate between crushers and mills and their appropriate uses.

1/ C – Central Idea: Detailing the construction and operational mechanics of various machines (crushers, mills) that employ different forces (compression, impact, attrition, cutting) to reduce the particle size of solid materials, and understanding their typical feed and product characteristics.

1/ D – Performance Objectives:

- By the end of this lecture, students will be able to describe the mechanical components and operating principles of at least two types of crushers.
- To describe the mechanical components and operating principles of at least two types of mills.
- To explain the type of force predominantly applied by each equipment discussed.
- To suggest suitable equipment for specific size reduction tasks based on material properties and desired product size.

2/ Pretest

- What's the main difference between breaking a large rock with a sledgehammer and grinding spices with a mortar and pestle?
- Why do some grinding machines have screens or grates?
- If you want to turn a boulder into sand, what type of machine would you start with?

Lecture Content

Building on our previous discussion about the principles and objectives of size reduction (comminution), this lecture delves into the specific types of equipment used in industrial settings. Chemical engineers must possess a thorough understanding of these machines to select, design, and operate size reduction systems effectively, ensuring optimal product quality, energy efficiency, and operational safety in refineries and chemical plants.

Size reduction equipment is generally categorized by the particle size they handle, from large crushers for coarse material to fine grinders and ultra-fine mills. The choice depends heavily on the feed material's characteristics (hardness, abrasiveness, friability, moisture), the desired product particle size distribution (PSD), and throughput requirements.

2. Crushers (Coarse to Intermediate Reduction)

Crushers are typically used for primary and secondary size reduction, handling large feed materials and producing coarser products. They primarily rely on **compression** and **impact** forces.

1. **Jaw Crushers:**
    - **Mechanism:** Material is fed into a V-shaped crushing chamber between a stationary jaw and a movable jaw. The movable jaw reciprocates, crushing the material against the stationary jaw.
    - **Key Features:** Characterized by their "gape" (opening at the top) and "set" (opening at the bottom). Types include Blake (pivot at top), Dodge (pivot at bottom), and overhead eccentric (pivot on eccentric shaft).
    - **Advantages:** Extremely robust, can handle very large and hard feed materials, high reduction ratio.
    - **Disadvantages:** Batch action (intermittent crushing), produces a non-uniform product, high vibration and noise.
    - **Refining/Chemical Applications:**
        - **Primary crushing of large coke lumps** discharged from **delayed coking units** to make them manageable for transport, storage, or subsequent processing like calcination.
        - Breaking up large agglomerates or lumps of **spent catalysts** for easier handling prior to regeneration or disposal.
2. **Gyratory Crushers:**
    - **Mechanism:** A conical crushing head rotates eccentrically within a stationary conical shell. Crushing occurs continuously around the entire circumference of the chamber.
    - **Key Features:** Similar crushing action to a jaw crusher but continuous.
    - **Advantages:** Higher capacity than jaw crushers for comparable sizes, continuous operation, produces a more uniform product than jaw crushers. Lower headroom compared to jaw.
    - **Disadvantages:** More complex mechanically, generally higher capital cost than jaw crushers.

- **Refining/Chemical Applications:** Less common *within* a typical petroleum refinery. However, in large chemical complexes or integrated mining-chemical operations (e.g., for processing mineral ores that are raw materials for chemicals), they are used for very high-throughput primary crushing of bulk solids.

3. **Roll Crushers (Smooth or Toothed):**
   - **Mechanism:** Material is fed between one or two rotating rolls. The material is drawn in by friction and crushed by compression. Toothed rolls enhance gripping for larger, harder materials.
   - **Key Features:** Can be single, double, or triple roll. The gap between the rolls directly controls the product size.
   - **Advantages:** Good control over product size distribution (produces fewer fines), relatively low dust generation, lower power consumption compared to impact crushers for certain applications.
   - **Disadvantages:** Limited reduction ratio per pass (often requires multiple stages), can be sensitive to sticky materials.
   - **Refining/Chemical Applications:** Crushing brittle materials like **limestone for flue gas desulfurization (FGDS) units**, pre-crushing for fine grinding of catalyst precursors, breaking up some friable chemical products.

3. Grinders/Mills (Intermediate to Fine Reduction)

Mills are designed for finer grinding, taking smaller feed from crushers and producing powders. They typically utilize **impact** and **attrition** forces.

1. **Hammer Mills:**
   - **Mechanism:** A rotor equipped with multiple free-swinging or fixed hammers rotates at high speed inside a grinding chamber. Material is broken by impact with the

hammers, and by attrition against grinding plates or screens lining the chamber. The product exits through a screen at the bottom.

- **Key Features:** Screen size determines the maximum product particle size. Can have fixed or swinging hammers.
- **Advantages:** Highly versatile for a wide range of materials (brittle, fibrous, crystalline), high throughput, relatively simple design and operation.
- **Disadvantages:** Produces a wide particle size distribution (generates significant fines), can be very dusty, high wear for abrasive materials, susceptible to damage from tramp metal.
- **Refining/Chemical Applications:**
  - **Pulverizing coal for boilers in refinery power generation plants**, ensuring efficient combustion.
  - Grinding various chemical additives and extenders.
  - Breaking up agglomerated or friable solid chemicals, or reclaiming and grinding some types of **spent catalysts** for specific downstream processes.

2. **Ball Mills / Rod Mills:**
   - **Mechanism:** A large, slowly rotating cylindrical shell (lined with wear-resistant material) is partially filled with grinding media (steel balls for ball mills, steel rods for rod mills). As the mill rotates, the media are lifted and then cascade or cataract, grinding the material primarily by **impact** (falling media) and **attrition** (rubbing action between media and particles). Can operate wet (with slurry) or dry (with air sweep).
   - **Key Features:** L/D (length-to-diameter) ratio affects grinding action. Critical speed (speed at which media would centrifuge). Can operate in open circuit (single pass) or closed circuit (with an external classifier to recycle oversized particles).

- **Advantages:** Can achieve very fine grinding (down to a few microns), handles highly abrasive and hard materials, high capacity, continuous operation.
- **Disadvantages:** Very high energy consumption, significant noise, considerable wear of grinding media (requires frequent replacement), large footprint, can generate substantial heat.
- **Refining/Chemical Applications: The primary workhorse for catalyst manufacturing and preparation.** This includes grinding various raw materials and support materials (e.g., alumina, silica, zeolites) to precise particle sizes required for optimal fluidization properties in FCC (Fluid Catalytic Cracking) catalysts, or to achieve desired surface areas and porosity for hydroprocessing or polymerization catalysts. Also used for grinding pigments and fillers used in petrochemical products.

3. **Attrition Mills (e.g., Pin Mills, Disc Mills, Vertical Roller Mills):**
    - **Mechanism:** Utilizes high shear forces, rubbing, and impact between rapidly rotating components (e.g., discs with pins, or rollers on a grinding table) to reduce particle size.
    - **Key Features:** Often operate with a narrow gap between rotating and stationary parts. Vertical roller mills are very common for coal and cement grinding, using large rollers compressing material on a rotating table.
    - **Advantages:** Can produce a narrow particle size distribution, efficient for soft to medium-hard materials, often integrated with classifiers.
    - **Disadvantages:** Not suitable for very hard or abrasive materials (high wear).
    - **Refining/Chemical Applications:** Grinding specialty chemicals, fine powders where precise PSD control is needed. Vertical roller mills are specifically used for

pulverizing coal in large power generation facilities associated with refineries or chemical complexes, known for their energy efficiency.

4. Ultrafine Grinders (Micronizers)

These mills are designed to achieve sub-micron particle sizes, often essential for high-performance materials.

1. **Fluid Energy Mills (Jet Mills):**
    - **Mechanism:** Material is fed into a grinding chamber where it is accelerated by high-velocity jets of compressed air, steam, or inert gas (e.g., nitrogen for reactive materials). Particle-to-particle collisions at very high speeds cause size reduction primarily by **impact** and **attrition**. There are no moving parts in the grinding zone.
    - **Key Features:** Operates on the principle of particle self-impingement. Can be configured as loop, oval, or opposed-jet mills.
    - **Advantages:** Produces extremely fine particles (sub-micron range, e.g., 0.5 to 10 µm), high product purity (no contamination from grinding media), excellent for **heat-sensitive materials** (due to gas expansion cooling), suitable for sterile or contained operations.
    - **Disadvantages:** Very high energy consumption (due to compressed gas), low throughput for the energy input, sensitive to feed characteristics, erosion of internal surfaces can be an issue with highly abrasive materials.
    - **Refining/Chemical Applications:**
        - **Production of highly specialized catalysts with very specific surface areas and ultrafine particle sizes** for advanced catalytic processes where high dispersion or rapid reaction kinetics are required.

- Grinding pigments, toners, and active pharmaceutical ingredients (APIs) where very high fineness is critical.

5. Chemical Engineering Considerations for Equipment Selection

The choice of size reduction equipment is a complex decision that requires a thorough understanding of the specific process needs:

1. **Feed and Product Particle Size Distribution (PSD):** The most critical factor. What is the range of feed sizes, and what is the target output PSD?
2. **Material Properties:**
    - **Hardness & Toughness:** Directly impacts the type of crusher/mill and wear rates.
    - **Abrasiveness:** Crucial for selecting wear-resistant materials for mill liners and grinding media (e.g., high-chromium steel, ceramic liners).
    - **Moisture Content & Stickiness:** High moisture or stickiness can cause material to cake, blind screens, or clog mills. Dry grinding might require pre-drying.
    - **Friability:** How easily the material shatters.
    - **Heat Sensitivity:** Some materials degrade with heat; jet mills or mills with cooling systems are needed.
    - **Combustibility/Explosivity:** Requires inert gas blanketing (e.g., nitrogen purging), explosion venting, and specific dust collection systems.
3. **Capacity and Throughput:** The required mass flow rate of material.
4. **Energy Efficiency:** A major operating cost. Comparing different mills using Bond Work Index and other energy data.
5. **Capital vs. Operating Costs:** Balancing the initial investment with ongoing energy, wear parts replacement, and maintenance.

6. **Safety and Environmental Considerations:** Dust control, noise levels, explosion hazards, and containment of hazardous materials are paramount.
7. **Maintenance:** Ease of access for cleaning, inspection, and replacement of wear parts (e.g., hammers, liners, grinding media).

4/ Posttest

- Explain the primary difference between a crusher and a mill in terms of their typical feed and product sizes.
- Describe the working principle of a Jaw Crusher and state the main force it uses.
- How does a Ball Mill achieve size reduction? What forces are involved?
- Which type of mill would you choose to produce ultra-fine powder for a pharmaceutical product, and why?

5/ Homework

- Research the "Cone Crusher" and compare its working principle and applications to the Gyratory Crusher.
- Draw a simple diagram of a Hammer Mill and label its main components.

6/ References

- "Unit Operations of Chemical Engineering" by McCabe, Smith, and Harriott.

- "Coulson & Richardson's Chemical Engineering, Vol 2: Particle Technology and Separation Processes".
- Industrial equipment manufacturers' websites (e.g., Metso, Sandvik, FLSmidth, Hosokawa Micron).

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Learning package

In

Size reduction equipment operation (Feed control, energy consumption , removal of heat

For

Students of First Year

By

Halah Kadhim Mohsin

Dep. Of Chemical industries Techniques

2025

1/ Overview

1/ A – Target Population: Technical institute students specializing in chemical technology, mineral processing, or industrial process operations.

1/ B – Rationale: To understand the practical aspects of operating size reduction equipment, focusing on key operational parameters such as feed management, energy efficiency, and thermal considerations, which are vital for optimizing performance and ensuring safety.

1/ C – Central Idea: Efficient size reduction involves careful control of material input, managing the significant energy input required, and addressing the heat generated during the mechanical breaking of solids to maintain equipment integrity and product quality.

1/ D – Performance Objectives:

- By the end of this lecture, students will be able to explain the importance of feed control in size reduction.
- To describe factors affecting energy consumption in crushers and mills.
- To identify the sources and implications of heat generation during size reduction.
- To list methods for removing heat from size reduction equipment.

2/ Pretest

- Why is it a bad idea to put too much material into a blender at once?
- Do you think it takes more energy to crush a big rock into gravel, or to grind that gravel into fine sand? Why?
- If you grind spices for a long time, what do you notice about the temperature of the grinder?

3/Lecture Content

1. Introduction

While the selection of appropriate size reduction equipment is a critical design decision, the efficient and safe operation of these machines is equally vital for achieving desired product specifications, minimizing operational costs, and ensuring equipment longevity in chemical plants and refineries. This lecture will focus on three key operational aspects: feed control, energy consumption, and heat removal.

2. Feed Control

Importance: Effective feed control is paramount for stable operation, consistent product quality, and maximizing the efficiency of size reduction equipment. Poor feed control can lead to:

- **Overloading:** Jamming the mill, causing motor trips, inefficient grinding, and excessive wear.
- **Underloading:** Reduced throughput, increased specific energy consumption (energy per unit of product), and potentially increased wear per unit of product.
- **Inconsistent Product Quality:** Fluctuations in particle size distribution.

- **Blockages and Fouling:** Particularly with sticky or moist materials.

Methods of Feed Control:

1. **Feeders:**
    - **Vibratory Feeders:** Use vibration to move material, suitable for a wide range of dry, granular materials.
    - **Screw Feeders:** Use a rotating screw to convey and regulate flow, effective for powders and sticky materials.
    - **Belt Feeders:** Provide precise control for larger volumes of bulk solids.
    - **Rotary Valves/Airlocks:** For feeding into pressurized or vacuum systems, often used in conjunction with pneumatic conveying systems.
    - **Weigh Belt Feeders:** Provide gravimetric control, ensuring a precise mass flow rate. **Chemical Engineering Significance:** Integration of variable speed drives with these feeders allows for dynamic adjustment of feed rate based on mill load or process requirements.
2. **Level Sensors/Load Cells:**
    - Sensors (e.g., ultrasonic, radar, load cells on hoppers) monitor the material level in feed bins or the weight of material being fed, providing feedback for automated feed rate adjustment.
    - **Mill Load Control:** For many mills (e.g., ball mills, vertical roller mills), the power drawn by the mill motor is directly proportional to the grinding load. This signal is often used as a primary control parameter to adjust the feed rate automatically, maintaining optimal grinding conditions and preventing overloading.
3. **Slurry Concentration (for Wet Grinding):**
    - For wet grinding (e.g., in ball mills for catalyst slurries), controlling the solids concentration (pulp density) in the feed slurry is critical. Too high a concentration can lead

to high viscosity and poor grinding, while too low can be inefficient. This is managed by controlling water addition.

3. Energy Consumption

Significance: Size reduction is among the most energy-intensive unit operations in the chemical and petroleum industries. Energy costs can represent a substantial portion of the overall operating expenditure. Optimizing energy consumption is a key objective for chemical engineers.

Factors Affecting Energy Consumption:

1. **Material Properties:** The inherent hardness, toughness, and abrasiveness of the material dictate the energy required (quantified by the **Bond Work Index** discussed in Lecture 10). Harder materials require significantly more energy.
2. **Degree of Reduction:** Reducing particle size to finer levels consumes disproportionately more energy. Breaking a particle from 100 µm to 10 µm requires far more energy than from 1000 µm to 100 µm.
3. **Mill Type and Efficiency:** Different mill types have varying energy efficiencies for specific applications and particle size ranges. For example, vertical roller mills are often more energy-efficient than ball mills for dry grinding coal.
4. **Operating Conditions:**
    - **Feed Rate:** Operating at optimal load is crucial. Underloading leads to wasted energy, and overloading to inefficiency and potential damage.
    - **Mill Speed:** For tumbling mills (ball/rod mills), operating at the correct percentage of critical speed maximizes grinding efficiency.
    - **Grinding Media Load:** Optimal loading of grinding media is essential for effective grinding.

- **Air Flow (for Air-Swept Mills/Jet Mills):** Correct air velocity and volume are needed for efficient grinding and material transport.

Optimizing Energy Consumption (Closed-Circuit Grinding):

- **Closed-Circuit Operation:** This is **the most crucial strategy** for minimizing energy consumption and achieving a narrow product particle size distribution.
  - **Mechanism:** The mill product is continuously fed to a **classifier** (e.g., screens for coarse products, air classifiers for fine powders). The classifier separates the finished product (undersize) from the oversized particles. The oversized particles are then recycled back to the mill for further grinding.
  - **Benefits:** Prevents overgrinding of already fine material (which is highly energy-intensive), ensures product quality, and significantly improves overall energy efficiency. **Chemical Engineering Role:** Design and implement robust control systems that integrate the mill, feeder, and classifier to achieve optimal grinding efficiency. Monitoring specific energy consumption (kWh/ton of product) is a key performance indicator.

4. Removal of Heat

Source of Heat: Almost all the mechanical energy supplied to a size reduction machine is converted into heat due to friction, inelastic deformation, and particle collisions. Only a very small fraction (typically less than 1%) goes into creating new surface area.

Consequences of Excessive Heat Buildup:

1. **Material Degradation:**
   - **Heat-Sensitive Materials:** Polymers, pharmaceuticals, certain catalysts (e.g., some fluid cracking catalysts) can

undergo thermal degradation, melting, caking, or losing desired properties (e.g., activity, porosity).
    - **Agglomeration/Stickiness:** Elevated temperatures can cause fine particles to become sticky and agglomerate, leading to poor flowability, mill clogging, and difficulty in separation.
2. **Equipment Damage:** Overheating of bearings, motors, and other mechanical components can lead to premature failure.
3. **Safety Hazards:** For combustible materials, increased temperature raises the risk of dust explosions (lower ignition temperature) and spontaneous combustion.

Methods of Heat Removal/Control:

1. **Cooling Jackets:** Applying cooling water or other coolants to the outer shell or specific sections of the grinding chamber (common in ball mills, stirred media mills).
2. **Cooling Air/Inert Gas:**
    - For **dry grinding**, introducing a controlled flow of cool air through the mill can sweep away heat and convey product.
    - For **combustible or reactive dusts (e.g., coal, many organic chemicals, some catalysts)**, **inert gas (e.g., nitrogen, CO2)** is crucial. It serves a dual purpose: it acts as a coolant and simultaneously provides an inert atmosphere to prevent dust explosions. This is particularly vital for fluid energy mills and pulverized coal mills.
3. **Refrigeration:** For highly heat-sensitive materials, sometimes the cooling fluid (air or jacket coolant) is pre-cooled via a refrigeration unit.
4. **Wet Grinding:** Using water as the grinding medium effectively dissipates heat.

5. **Optimizing Throughput:** Maintaining a consistent, optimal feed rate helps distribute heat generation and prevents localized overheating.
6. **Controlled Mill Speed:** Reducing the speed of the mill can decrease the rate of heat generation, though it also reduces grinding efficiency. **Chemical Engineering Significance:** Designing efficient cooling systems, selecting the appropriate grinding environment (dry vs. wet, inert atmosphere), and continuously monitoring temperatures within the mill are vital responsibilities.

5. Wear and Maintenance

Significance: Size reduction operations involve severe abrasive and impact forces, leading to significant wear on critical mill components. This translates directly to high maintenance costs and potential downtime.

Factors Contributing to Wear:

- **Material Abrasiveness:** The inherent hardness and sharpness of the material being ground.
- **Operating Speed:** Higher speeds generally lead to increased impact forces and wear.
- **Grinding Mechanism:** Impact and attrition cause more wear than pure compression.
- **Grinding Media (for Ball/Rod Mills):** Consumption of grinding media is a major operating cost and wear on liners.

Mitigation and Chemical Engineering Role:

- **Material Selection:** Specifying wear-resistant materials for mill liners, hammers, screens, and grinding media (e.g., high-manganese steel, chrome alloys, ceramic liners, rubber liners).
- **Design Optimization:** Designing grinding chambers and flow paths to minimize direct impact on non-wearing parts.

- **Routine Inspection and Planned Maintenance:** Regular checks for wear, replacement of worn parts during scheduled shutdowns, and analysis of wear patterns to inform future design improvements.
- **Media Management:** For ball/rod mills, optimizing media size and composition, and managing media top-up rates.

6. Dust Control and Safety

Recap and Deeper Dive: Beyond process efficiency, safety and environmental compliance are paramount in size reduction operations due to the generation of fine dust.

- **Dust Emissions:** Fine dust escaping from mills or conveying systems is an environmental pollutant and a product loss.
    - **Mitigation:** Enclosed systems, effective sealing, and **dust collection systems** (e.g., cyclones as primary separators, followed by baghouses for fine particulate removal) are essential for capturing and recovering dust, ensuring environmental compliance.
- **Dust Explosions:** This is a critical safety hazard for many finely divided solid materials (e.g., pulverized coal, many organic chemicals, polymer powders, some catalysts).
    - **Conditions for Explosion:** Fuel (combustible dust), Oxidant (air), Ignition Source (spark, hot surface, static electricity), Dispersion (dust cloud), Confinement.
    - **Mitigation (Chemical Engineering Responsibility):**
        - **Inerting: Blanketing the grinding system with an inert gas (e.g., nitrogen) to reduce oxygen concentration below the lower explosive limit (LEL).** This is a primary explosion prevention method.
        - **Explosion Venting:** Designing and installing rupture panels or vents to safely relieve explosion

pressure, preventing catastrophic structural damage.
        - **Explosion Suppression Systems:** Rapidly injecting a fire retardant into the vessel to extinguish an incipient explosion.
        - **Bonding and Grounding:** Preventing static electricity buildup, which can be an ignition source.
        - **Minimizing Dust Accumulation:** Good housekeeping to prevent fugitive dust layers that can propagate explosions.
        - **Electrical Classification:** Using explosion-proof electrical equipment in hazardous areas.
- **Noise:** Size reduction equipment generates significant noise.
    - **Mitigation:** Engineering controls (enclosures, acoustic insulation) and administrative controls (hearing protection for personnel, limited exposure times).

Conclusion: Optimal operation of size reduction equipment is a complex undertaking that balances achieving the desired particle size distribution with minimizing energy consumption, controlling heat generation, managing wear, and, most importantly, ensuring a safe and environmentally compliant operation. This requires continuous monitoring, process adjustments, and a robust understanding of both the equipment and the material properties.

4/ Posttest

- Explain why precise feed control is essential for optimal size reduction.
- List three factors that significantly affect the energy consumption of a size reduction machine.

- What are two potential problems caused by excessive heat generation during grinding?
- Describe two different methods used to remove heat from size reduction equipment.

5/ Homework

- Imagine you are designing a process to grind a heat-sensitive pharmaceutical powder. What specific considerations regarding heat removal would you prioritize, and why?
- Explain the concept of "specific energy consumption" in size reduction. Why is it important to minimize it?

6/ References

- "Unit Operations of Chemical Engineering" by McCabe, Smith, and Harriott.
- "Chemical Process Engineering: Design and Economics" by Harry S. C. Fogler.
- Technical manuals from manufacturers of crushers and mills.

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Technological institute of Basra
Department of Chemical Industries Techniques

Learning package

In

Mixing of solids and pastes

For

Students of First Year

By

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Dep. Of Chemical industries Techniques

2025

1/ Overview

1/ A – Target Population: Technical institute students specializing in chemical technology, food processing, pharmaceutical production, or any industry handling fluid or solid mixtures.

1/ B – Rationale: To understand the fundamental principles and equipment used for mixing various materials, which is a critical operation for achieving uniformity and facilitating reactions or processes in many industries.

1/ C – Central Idea: The process of combining different materials (liquids, solids, or gases) to achieve a uniform distribution of components throughout the mixture, thereby enhancing mass transfer, heat transfer, or chemical reactions.

1/ D – Performance Objectives:

- By the end of this lecture, students will be able to define mixing and its importance.
- To explain the main objectives of mixing in different industrial applications.
- To identify the basic types of mixing equipment for liquids and solids.
- To understand the role of impellers and baffles in liquid mixing.

2/ Pretest

- If you put sugar in your coffee, what do you do to make it dissolve faster?
- Why do bakers mix flour, water, and yeast to make dough?

- What is the difference between a liquid and a solid?

3/Lecture Content

1. Introduction to Mixing

Definition: Mixing is a critical unit operation in chemical engineering that involves the randomizing or blending of two or more distinct phases (solids, liquids, gases) to achieve a desired level of uniformity. In this lecture, we focus specifically on the mixing of solid particles (powders and granules) and highly viscous materials (pastes).

Chemical Engineering Significance: The effectiveness of mixing directly impacts the efficiency and success of numerous chemical processes:

- **Uniform Reactions:** Ensuring reactants are evenly distributed to achieve consistent reaction rates, higher yields, and prevent localized overheating or side reactions.
- **Consistent Product Quality:** Guaranteeing that the final product meets specifications for composition, appearance, dissolution rate, and performance.
- **Improved Heat and Mass Transfer:** Enhancing contact between phases for processes like drying, adsorption, dissolution, or heterogeneous catalysis.
- **Dispersion of Active Ingredients:** Distributing small amounts of critical components (e.g., catalysts, pigments, active pharmaceutical ingredients) uniformly throughout a bulk material.
- **Homogenization:** Blending different batches or types of raw materials to create a uniform feedstock.

2. Fundamentals of Solid Mixing (Dry Powders and Granules)

Mixing of solids is fundamentally different from liquid mixing due to the discrete nature of particles and the absence of fluid flow.

Mechanisms of Solid Mixing:

1. **Convective Mixing (Macro-mixing):**
    - Involves the transfer of large groups of particles from one location to another within the mixer. This creates macroscopic uniformity.
    - Example: Tumbling mixers where the entire bed of particles is rearranged.
2. **Shear Mixing:**
    - Creation of slip planes or shear zones within the bed of particles, leading to localized rearrangement and inter-particle movement.
    - Example: Ribbon blenders where helical ribbons move particles in different directions, causing shear between adjacent layers.
3. **Diffusive Mixing (Micro-mixing):**
    - Refers to the random movement of individual particles within the bulk of the powder bed, often driven by gravity or very mild agitation. This mechanism is responsible for true microscopic homogeneity.
    - Example: Particles rolling down a heap in a tumbling mixer.

Degree of Mixing (Homogeneity): For chemical engineers, quantifying the degree of mixing is essential for quality control. It's typically expressed statistically using the variance of component concentrations measured at different points in the mixture. The goal is often to achieve a "random mix," where the probability of finding a particle of a given component is the same everywhere.

Factors Affecting Solid Mixing (Chemical Engineering Perspective):

1. **Particle Properties:** The most critical factors influencing solid mixing and segregation.
    - **Size:** Larger differences in particle size increase segregation tendencies.
    - **Shape:** Irregular shapes can promote interlocking and reduce segregation, while spherical particles are more prone to segregation.
    - **Density:** Differences in particle density lead to segregation (denser particles settling).
    - **Cohesiveness/Adhesiveness:** Electrostatic charges or moisture can cause particles to stick together, making mixing difficult but reducing segregation.
    - **Surface Roughness:** Can affect inter-particle friction.
    - **Moisture Content:** Small amounts can increase cohesiveness, large amounts can lead to caking.
2. **Segregation Tendencies (A Major Challenge):**
    - Segregation (un-mixing) is the opposite of mixing and is a pervasive problem in solid handling. It occurs when particles separate after mixing due to differences in their physical properties.
    - **Mechanisms of Segregation:**
        - **Percolation (Sifting):** Finer particles sift down through voids between larger particles.
        - **Trajectory Segregation:** Larger, heavier particles tend to roll further down inclines or have greater inertia during movement.
        - **Elutriation (Air Entrainment):** Finer, lighter particles can become airborne and settle separately or be carried away by air currents.
    - **Chemical Engineering Mitigation:** Selecting the right mixer, careful design of conveying systems, adding

binders, controlling moisture, and avoiding excessive handling after mixing.

3. **Mixer Type and Design:** Choosing a mixer suited for the material properties and desired mixing mechanism.
4. **Mixing Time:** Sufficient time is needed to achieve the target homogeneity. Over-mixing can sometimes lead to segregation.
5. **Fill Level:** The optimal fill level in a mixer is crucial for efficient particle movement.

3. Equipment for Mixing Solids (Dry Powders and Granules)

These mixers primarily handle free-flowing to moderately cohesive dry powders and granular materials.

1. **Tumbling Mixers (Convective Mixing):**
    - **V-Blender / Double Cone Blender:**
        - **Mechanism:** A V-shaped or double-cone vessel rotates on a horizontal axis, causing the material to tumble and divide repeatedly.
        - **Advantages:** Very gentle mixing (low shear), excellent for fragile or abrasive particles, easy to clean, low energy consumption.
        - **Disadvantages:** Relatively long mixing times, limited for very cohesive powders or those requiring high shear.
        - **Chemical Engineering Applications:**
            - **Blending powders for catalyst formulation** where particle integrity is crucial.
            - Mixing **polymer pellets with additives** (e.g., stabilizers, colorants).
            - Dry blending of pharmaceuticals, food ingredients, and other sensitive fine chemicals.
2. **Convective Mixers (Stationary Shell with Internal Agitator):**

- **Ribbon Blender:**
  - **Mechanism:** A horizontal trough mixer with inner and outer helical ribbons mounted on a central shaft. The ribbons move material in opposing directions, creating both axial and radial flow patterns.
  - **Advantages:** Good for free-flowing to slightly cohesive powders, can handle liquids sprayed onto powders (e.g., for coating or granulation), provides moderate shear.
  - **Disadvantages:** Limited for very sticky or very fine powders (may form lumps), discharge can be incomplete.
  - **Chemical Engineering Applications:**
    - Blending powdered chemicals like **detergent ingredients, fertilizers, or specialty chemical precursors**.
    - Incorporating **liquid binders or lubricants into catalyst precursors** before extrusion.
    - Blending **dry pigment powders**.
- **Vertical Screw Mixer (Nauta Mixer):**
  - **Mechanism:** A conical vessel with a rotating screw that orbits around the cone's inner wall. This lifts material from the bottom and gently deposits it onto the top, creating a spiral mixing action.
  - **Advantages:** Extremely gentle, ideal for fragile particles, suitable for very large batch volumes, good for heat-sensitive materials (often jacketed for cooling).
  - **Disadvantages:** Long mixing times, high headroom required.
  - **Chemical Engineering Applications:**
    - Blending **fragile polymers or catalyst supports**.

        - Large-scale blending of powders where gentle handling and low shear are critical.

4. Mixing of Pastes and Viscous Materials

Pastes and highly viscous materials present unique challenges due to their limited fluidity and high resistance to flow. Mixing these materials primarily relies on intensive **shear** and **kneading** forces.

Challenges:

- **High Power Consumption:** Due to high viscosity.
- **Difficulty in Homogeneity:** Material flow is laminar; no turbulent or diffusive mixing.
- **Heat Generation:** Significant mechanical energy is converted to heat, requiring cooling.

Equipment for Mixing Pastes:

1. **Sigma Blade Mixer (Kneader):**
    - **Mechanism:** Consists of two Z-shaped blades rotating in a trough at differential speeds (one faster than the other). The blades repeatedly cut, shear, and fold the material against each other and the trough walls.
    - **Advantages:** Excellent for very high viscosity materials (e.g., 500 to 500,000 P or more), provides intense shear and kneading action, good for dispersion of solids into pastes.
    - **Disadvantages:** Batch operation, high power consumption, difficult to clean due to complex blade geometry, often generates significant heat.
    - **Chemical Engineering Applications:**
        - **Mixing highly viscous catalyst pastes** that are subsequently extruded or pelletized into shaped catalysts (e.g., for hydrotreating, reforming).

        - Compounding **polymers with high loadings of fillers or additives** (e.g., masterbatches).
        - Mixing adhesives, sealants, ceramic pastes, and highly concentrated slurries.
2. **Planetary Mixer:**
    - **Mechanism:** One or more mixing blades (e.g., paddle, whisk) rotate on their own axis while simultaneously orbiting around the inside of a stationary mixing bowl. This ensures that the entire volume of material is thoroughly mixed, with no dead spots.
    - **Advantages:** Good for medium to high viscosity materials (e.g., 100 to 50,000 P), versatile for various products, ensures thorough mixing with minimal unmixed zones.
    - **Disadvantages:** Batch operation, can be high power for very viscous materials.
    - **Chemical Engineering Applications:** Mixing slurries, light pastes, ointments, resin compounds, batches of paints, and specialized chemical formulations.
3. **Extruders (Single and Twin Screw Extruders):**
    - **Mechanism:** One or two intermeshing screws rotate within a heated barrel. The screw geometry (e.g., conveying elements, mixing elements, kneading blocks) is specifically designed to convey, melt (for polymers), and intensively mix (through shear and distributive action) highly viscous materials.
    - **Advantages: Continuous operation**, excellent for high shear mixing and compounding, can handle reactive mixing (reactive extrusion), good for devolatilization.
    - **Disadvantages:** High capital cost, specialized equipment, complex to operate and clean compared to batch mixers.
    - **Chemical Engineering Applications:**
        - **Polymer compounding:** The dominant method for incorporating additives, fillers, pigments, and other

components into polymer melts, ensuring uniform dispersion before pelletization. **This is a major application in the petrochemical industry.**

- **Reactive extrusion:** Performing chemical reactions within the extruder (e.g., polymerization, grafting).
- **Preparing catalyst precursors for shaped catalysts:** Extruding catalyst pastes into specific shapes (e.g., pellets, rings) and providing initial mixing before drying and calcination.

5. Chemical Engineering Design & Operational Considerations

1. **Desired Degree of Mixing:** This dictates the mixer type, mixing time, and necessary power input. It's tied directly to product quality specifications and reaction uniformity.
2. **Material Properties:** As discussed, this is the paramount factor. Chemical engineers must characterize the rheology (viscosity, yield stress) of pastes, and the physical properties (PSD, density, cohesiveness) of powders to select the right mixer and predict its performance.
3. **Segregation Mitigation:** For solid mixtures, chemical engineers must actively design processes to prevent segregation:
    - Selecting mixers that minimize segregation (e.g., avoiding over-mixing in tumbling mixers).
    - Controlling the particle size distribution of feed materials.
    - Adding small amounts of binders or liquids to increase cohesiveness.
    - Minimizing transfer points and drops after mixing to prevent un-mixing during handling.
4. **Scale-Up:** Scaling up mixing operations from lab to industrial scale is challenging. Principles of geometric similarity, power

per unit volume, and mixing time must be carefully considered.

5. **Energy Consumption:** High power consumption, especially for paste mixers. Energy efficiency is a key design criterion.
6. **Heat Generation and Removal:** Intensive shear in paste mixing generates significant heat. Cooling jackets on mixers or controlled operating parameters may be needed to maintain product integrity and prevent degradation.
7. **Batch vs. Continuous Operation:** The choice depends on production volume, process flexibility, and quality control requirements. Continuous mixers (e.g., extruders) are for large, steady throughputs.
8. **Cleaning and Maintenance:** Ease of cleaning is vital, especially for sticky materials or when changing products to prevent cross-contamination. Wear on agitators and mixing elements needs to be managed.
9. **Safety:**
    - **Dust Explosions:** For mixing combustible powders, inerting (e.g., nitrogen purging), explosion venting, and proper grounding are essential.
    - **Ergonomics and Material Handling:** Designing for safe loading and unloading of materials.

6. Relevance to Chemical Engineering & Petroleum Refining

- **Catalyst Production:** One of the most significant applications. Blending various catalyst components (active metals, promoters, support materials like alumina, silica, zeolites) to achieve a homogeneous mixture before subsequent processing steps (e.g., impregnation, drying, calcination). Intensive mixing of **catalyst pastes** is crucial for forming shaped catalysts (e.g., extrudates, pellets) used in fixed-bed reactors throughout refineries.
- **Polymer Compounding:** A major operation in the petrochemical industry. Mixing various additives (e.g.,

stabilizers, antioxidants, pigments, flame retardants, fillers) into polymer melts or powders using high-shear mixers like extruders or kneaders to achieve desired final product properties.

- **Specialty Chemical Blending:** Creating homogeneous mixtures of various solid chemical products, such as detergents, fertilizers, agrochemicals, or powdered paints.
- **Additive Blending for Fuels and Lubricants:** While often liquid blending, some solid additives may need to be mixed into a carrier fluid or pre-blended as powders before final dispersion.
- **Waste Treatment:** Mixing sludges or solid waste with conditioning chemicals (e.g., lime) to prepare them for dewatering or disposal.

4/ Posttest

- Define mixing and explain why uniformity is a key objective.
- List two reasons why mixing is important in industrial processes.
- What are impellers and baffles, and what is their role in liquid mixing?
- Name one type of equipment used for liquid mixing and one type for solid-solid mixing.

5/ Homework

- Think about a food product you consume daily (e.g., yogurt, bread, soup). Describe where mixing might be used in its production process.
- Explain why trying to mix two liquids with very different viscosities (like honey and water) might require different mixing equipment compared to mixing two liquids with similar viscosities.

6/ References

- "Unit Operations of Chemical Engineering" by McCabe, Smith, and Harriott (or similar standard textbook).
- "Chemical Process Equipment: Selection and Design" by James R. Couper, et al.
- Manufacturer's literature and online resources on industrial mixers and blenders.

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Materials handling

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1/ Overview

1/ A – Target Population: Technical institute students specializing in chemical technology, manufacturing, logistics, or any industrial field involving the movement and management of materials.

1/ B – Rationale: To understand the fundamental principles and various types of equipment used for the safe, efficient, and cost-effective movement, storage, and control of materials throughout industrial processes and supply chains.

1/ C – Central Idea: Materials handling is the art and science of moving, packing, and storing materials in any form, focusing on minimizing costs, optimizing space, ensuring safety, and improving overall operational efficiency from raw material intake to finished product dispatch.

1/ D – Performance Objectives:

- By the end of this lecture, students will be able to define materials handling and explain its importance in industry.
- To identify the main objectives of efficient materials handling.
- To describe different types of equipment used for moving bulk solids, liquids, and discrete units.

- To understand basic principles of materials handling system design.

2/ Pretest

- What happens if you try to carry too many boxes at once?
- How does a conveyor belt help move things in a supermarket checkout?
- If you want to move water from one tank to another, what machine would you use?

3/Lecture Content

1. Introduction to Materials Handling

Definition: Materials handling encompasses the entire system of movement, storage, protection, and control of materials throughout the manufacturing process, from the receipt of raw materials to the shipment of finished products. It involves not just the equipment, but also the methods, personnel, and overall layout of a facility.

Chemical Engineering Significance: For chemical engineers, efficient materials handling is far more than just logistics; it is integral to process design, optimization, and safety. It profoundly impacts:

- **Process Continuity and Bottlenecks:** Smooth material flow prevents costly interruptions in production.

- **Product Quality and Integrity:** Preventing contamination, degradation (e.g., polymer shearing, catalyst attrition), segregation of mixtures, or moisture pickup during transport.
- **Safety:** Safely handling hazardous, flammable, explosive, toxic, or high-temperature materials is a paramount concern in refineries and chemical plants.
- **Operational Efficiency and Plant Layout:** An optimized handling system minimizes distances, reduces labor, and improves overall plant productivity.
- **Cost Minimization:** Reduces labor costs, energy consumption, inventory holding costs, and waste generation.
- **Integration of Unit Operations:** Materials handling systems are the arteries connecting various unit operations (e.g., reactors, separators, mixers, dryers) into a cohesive process.

2. Classification of Materials to be Handled

The properties of the materials dictate the choice of handling equipment and system design.

1. **Solids:**
    - **Bulk Solids:** Powders, granules, pellets, chips, lumps (e.g., catalysts, polymer pellets, coal, coke, fertilizers, pigments).
        - **Key Properties (Chemical Engineering Relevance):**
            - **Flowability:** How easily material flows (affected by particle size, shape, moisture, cohesiveness, angle of repose). Poor flowability leads to arching and rat-holing in hoppers.
            - **Abrasiveness:** Causes wear on equipment.
            - **Cohesiveness/Stickiness:** Can lead to caking and buildup.

        - **Dustiness:** Environmental and safety (explosion) hazard.
        - **Moisture Content:** Impacts flowability, can cause caking or degradation.
        - **Heat Sensitivity:** Some materials degrade or melt if exposed to high temperatures during handling.
        - **Combustibility/Explosivity:** Critical safety concern requiring inerting and explosion protection.
    - **Unit Loads:** Sacks, drums, bags, intermediate bulk containers (FIBCs), boxes (e.g., bagged specialty chemicals, catalyst drums, finished product bags).
2. **Liquids:** (While outside the primary scope of this lecture focused on solids, it's worth noting.) Viscosity, corrosivity, volatility, flammability, toxicity. Handled by pumps, pipes, tanks.
3. **Gases:** (Also briefly mentioned.) Pressure, temperature, corrosivity, flammability. Handled by compressors, pipes, vessels.

3. Principles of Materials Handling (Chemical Engineering Viewpoint)

These principles guide the design and operation of efficient and safe material handling systems in process industries:

- **Unit Load Principle:** Handle materials in larger, consolidated unit loads (e.g., using bulk bags instead of many small sacks) to minimize the number of individual handling actions, thereby reducing labor and time.
- **Flow Principle:** Design systems to ensure a continuous, uninterrupted material flow wherever possible, preventing bottlenecks and maximizing throughput.

- **Simplification Principle:** Eliminate, combine, or reduce unnecessary handling steps and equipment.
- **Safety Principle:** Design systems to minimize risks associated with material properties (e.g., dust explosions, toxic exposures, flammability) and equipment operation.
- **Ergonomic Principle:** Consider human factors in design to ensure ease of operation, minimize fatigue, and prevent injuries.
- **Environmental Principle:** Design systems to minimize dust emissions, spills, waste generation, and noise pollution.
- **Space Utilization Principle:** Efficiently use the available plant space for both material movement pathways and storage areas.
- **Mechanization/Automation Principle:** Utilize mechanical or automated equipment for repetitive, hazardous, or high-volume tasks to reduce labor and improve consistency.

4. Equipment for Materials Handling (Focus on Solids and Pastes)

1. **Conveyors (Continuous Movement):** Designed for continuous, often high-volume, transport of materials over various distances and elevations.
    - **Belt Conveyors:**
        - **Mechanism:** A continuous loop of flexible belt supported by idler rollers, moving material from one point to another.
        - **Advantages:** High capacity, capable of long distances, versatile for various bulk materials (granular, lumpy), relatively low maintenance for non-abrasive materials.
        - **Disadvantages:** Open design can lead to dust emissions and spillage (unless enclosed), limited steepness of incline.
        - **Chemical Engineering Applications:**

        - Transporting **coal to refinery power plants or chemical complexes** for energy generation.
        - Moving large volumes of **green coke from delayed coking units** to storage piles or calcination units.
        - Conveying **polymer pellets** from polymerization units to storage silos or packaging.
        - Transport of granular fertilizers, bulk catalyst, and other large-volume granular materials.
    - **Screw Conveyors:**
        - **Mechanism:** A helical screw (auger) rotates within a fixed trough or tube, pushing material along.
        - **Advantages:** Fully enclosed (excellent for dusty, hazardous, or odorous materials), versatile for powders, granules, and even sticky sludges/pastes, relatively compact.
        - **Disadvantages:** Limited length (multiple units needed for long distances), lower capacity than belt conveyors for bulk solids, material can compact and degrade, high wear for abrasive materials.
        - **Chemical Engineering Applications:**
            - Moving **fine catalyst powders or other additives** within a processing unit.
            - Feeding precise amounts of powders to reactors, mixers, or mills.
            - Handling **sticky sludges or filter cakes** from dewatering operations (e.g., from filter presses).
            - Conveying **spent catalysts** in enclosed systems.
    - **Bucket Elevators:**

        - **Mechanism:** Buckets mounted on a continuous belt or chain, moving vertically to lift bulk solids.
        - **Advantages:** Efficient for vertical lifting, compact footprint for vertical transport.
        - **Disadvantages:** Can cause attrition and degradation for fragile materials, maintenance can be more complex than horizontal conveyors.
        - **Chemical Engineering Applications:** Lifting bulk solids such as **catalyst particles (e.g., FCC fresh catalyst)**, coal, coke, or cement to elevated hoppers or silos for gravity feeding into process units.
    - **Pneumatic Conveying Systems:**
        - **Mechanism:** Material is suspended and transported in a gas stream (usually air, but often inert gas like nitrogen for safety). Can be dilute phase (material entrained) or dense phase (material plugs).
        - **Advantages:** Fully enclosed and dust-free, highly flexible routing (can go around corners), no moving parts in contact with the material (except for blowers/fans), ideal for fine powders and granules. Excellent for hazardous or explosive materials when using inert gas.
        - **Disadvantages:** High energy consumption (for gas compression), potential for erosion of pipes (especially with abrasive materials), material degradation (attrition, thermal degradation from friction), static electricity buildup.
        - **Chemical Engineering Applications:**
            - **Crucial for handling fine catalyst powders, especially in Fluid Catalytic Cracking (FCC) units**, where fresh, spent, and regenerated catalysts are pneumatically

transported between reactor, regenerator, and storage silos.
        - Conveying highly active, corrosive, or explosive powders **(using inert nitrogen gas as the conveying medium)**.
        - Transporting granular polymers, carbon black, and other fine particulate solids.
2. **Feeders (Controlled Flow - Recap):**
    - While mentioned under size reduction, feeders are fundamental materials handling equipment designed to provide a controlled, consistent flow of material from a hopper or bin into a processing unit. Types include vibratory feeders, rotary valves, screw feeders, and weigh feeders.
    - **CE Relevance:** Essential for regulating material flow into reactors, blenders, mills, and dryers to ensure stable operation, precise stoichiometry, and consistent product quality.
3. **Hoppers and Silos (Storage & Discharge):**
    - **Mechanism:** Vertical vessels with a converging (conical or pyramidal) bottom, designed for the temporary storage and controlled discharge of bulk solids. Silos are typically larger.
    - **Key Design Considerations (Chemical Engineering):**
        - **Flowability:** Designing the hopper angle and outlet size to ensure reliable flow and prevent common issues like **arching (material forms a stable bridge)** and **rat-holing (material flows only through a narrow channel above the outlet)**. These are critical for process continuity.
        - **Mass Flow vs. Funnel Flow:** Mass flow design (all material moves when some is drawn out) is preferred for sticky or fine materials to prevent segregation and spoilage. Funnel flow (only a

channel flows) can lead to stagnant zones and segregation.
        - **Material Compatibility:** Materials of construction to prevent corrosion, abrasion, or contamination.
        - **Prevention of Segregation:** Especially in mass flow designs, controlling filling and discharge patterns to minimize particle separation.
    - **Chemical Engineering Applications:** Intermediate storage for **catalyst particles, polymer pellets, coal, coke, various solid additives, and finished chemical products.**
4. **Bulk Bag (Flexible Intermediate Bulk Container - FIBC) Handling Systems:**
    - **Mechanism:** Large, woven flexible containers (typically holding 1 to 2 tons) designed for easy filling, transport (via forklift or crane), and controlled discharge.
    - **Advantages:** Cost-effective for intermediate volumes, reduces labor compared to small bags, can be designed for safe filling and discharge.
    - **Disadvantages:** Requires specialized handling equipment (forklifts, hoists, bulk bag dischargers).
    - **Chemical Engineering Applications:** Transporting and storing **bagged catalysts, specialty chemicals, polymer granules, and other powdered/granular raw materials or finished products** in a contained manner.

5. Chemical Engineering Design & Operational Considerations

1. **Comprehensive Material Characterization:** This is the foundational step. Engineers must understand a material's flowability, abrasiveness, cohesiveness, angle of repose, particle size distribution, bulk density, dustiness, hygroscopicity (moisture absorption), corrosivity, heat sensitivity, and **explosivity parameters (e.g., Kst value,**

Minimum Ignition Energy - MIE). This dictates equipment choice, sizing, and safety features.

2. **Process Integration and Layout:** Designing the entire handling system as an integrated part of the plant layout, ensuring smooth connections between unit operations, minimizing transfer points, and optimizing flow paths.
3. **Safety:**
    - **Dust Explosions:** For combustible powders, implementing **inerting systems (e.g., nitrogen blanketing)** in silos and conveying lines, **explosion venting or suppression systems**, proper **bonding and grounding** to prevent static buildup, and rigorous **housekeeping** to prevent dust accumulation. This is paramount in many chemical plants and refineries (e.g., coal pulverization, polymer handling).
    - **Toxicity/Hazardous Materials:** Using fully enclosed conveying systems, proper ventilation, and containment strategies to minimize operator exposure.
    - **Fire Hazards:** Designing systems to prevent friction-induced heat buildup, and ensuring appropriate fire suppression.
    - **Ergonomics:** Designing equipment for safe and easy loading, unloading, and maintenance.
4. **Environmental Control:** Minimizing fugitive dust emissions through enclosed systems, dust collection (cyclones, baghouses), and careful transfer point design. Preventing spills.
5. **Contamination and Degradation:** Selecting appropriate materials of construction for equipment to prevent product contamination. Designing for gentle handling to prevent material degradation (e.g., attrition of fragile catalysts in pneumatic conveyors, shearing of polymer pellets).
6. **Energy Efficiency:** Optimizing conveyor speeds, selecting energy-efficient fans/blowers for pneumatic systems, and minimizing unnecessary lifts.

7. **Maintenance:** Implementing robust maintenance schedules to address wear from abrasive materials, lubricate moving parts, and inspect equipment integrity.
8. **Automation and Control:** Utilizing sensors (level, flow, pressure, temperature) and control systems to automate material flow, optimize feeding, and ensure safe operation.

6. Relevance to Petroleum Refining and Petrochemicals

- **Catalyst Management:** A cornerstone application. This includes:
  - **Receiving and transporting fresh catalysts** from bags/drums to silos, often via pneumatic conveying or bucket elevators.
  - **Feeding catalysts to reactors** (e.g., FCC, hydrotreaters) using various feeder types.
  - **Handling spent and regenerated catalysts** (pneumatically in FCC units, or by screw/belt conveyors for fixed-bed catalysts) to and from regenerators, storage, or disposal.
- **Coke Handling:** Transporting green coke (solid residue from delayed coking) from the coker drums to storage piles, calcination units, or loading facilities, primarily using robust belt conveyors and bucket elevators.
- **Coal Handling:** For refineries or chemical plants with their own power generation, large-scale systems involving belt conveyors, bucket elevators, and sometimes pneumatic conveyors are used to transport coal from receipt to pulverizers and then to boilers.
- **Polymer Production:** Handling and conveying polymer pellets or powders from polymerization reactors to extruders, storage silos, and packaging lines. This often involves pneumatic conveying, belt conveyors, and large storage silos.

- **Additive and Filler Handling:** Transporting various solid additives (e.g., anti-oxidants, pigments, UV stabilizers) used in petrochemical products to blending and compounding units.
- **Waste Solids Handling:** Managing the transport of industrial sludges (e.g., from wastewater treatment) or other solid wastes for dewatering, further processing, or disposal.

4/ Posttest

- Define materials handling and state two main objectives of efficient materials handling.
- Name two types of conveyors used for bulk solids and briefly explain how one of them works.
- What is a forklift used for, and why is it important in a warehouse?
- List three different forms in which materials can be handled.

5/ Homework

- Choose a specific industrial plant (e.g., a car manufacturing plant, a food canning factory). Describe at least three different materials handling equipment types you expect to find there and what materials they would handle.
- Explain why the "Unit Load Principle" is important in modern logistics and warehousing.

6/ References

- "Materials Handling: Principles and Practice" by Michael P. Deisenroth.
- "Facilities Planning" by James A. Tompkins and John A. White.
- "Production and Operations Management" by Jay Heizer and Barry Render.
- Industry standards and guidelines for materials handling and safety.

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Storage

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1/ Overview

1/ A – Target Population: Technical institute students specializing in chemical technology, manufacturing, logistics, supply chain management, or any industrial field involving inventory management.

1/ B – Rationale: To understand the critical role of storage in industrial operations and supply chains, covering different types of storage systems, their design considerations, and their impact on efficiency, cost, and product integrity.

1/ C – Central Idea: Storage is the planned retention of materials for a period of time, acting as a buffer in the production and distribution process to balance supply and demand, protect product quality, and optimize operational flow.

1/ D – Performance Objectives:

- By the end of this lecture, students will be able to define storage and its main functions in industry.
- To explain the difference between static and dynamic storage.
- To identify common types of storage equipment and systems for different material forms.
- To describe key considerations for designing or managing an effective storage area.

2/ Pretest

- Where do you keep extra food at home? Why don't you keep it all on the kitchen counter?

- If a factory produces cars faster than they can be sold, what happens to the extra cars?
- Why is it important to know exactly where things are stored in a large warehouse?

3/Lecture Content

1. Introduction to Storage

Definition: Storage, within the context of chemical engineering, refers to the systematic containment of raw materials, intermediate products, and finished goods for varying durations within a processing facility. While closely linked to materials handling (which focuses on movement), storage is about holding materials efficiently, safely, and securely.

Chemical Engineering Significance: Storage is a strategically vital aspect of plant design and operation in refineries and chemical plants, serving several critical functions:

- **Raw Material Buffer:** Provides a steady supply of feedstocks to processing units, decoupling production from the fluctuating schedules of raw material deliveries. This prevents costly shutdowns due to supply interruptions.
- **Intermediate Product Buffer (Inter-Stage Storage):** Allows sequential process steps to operate independently at their optimal rates. For example, a reaction section might produce material faster than a downstream separation unit can process it, requiring intermediate storage. This improves overall plant flexibility and efficiency.
- **Finished Product Buffer:** Accommodates discrepancies between production rates and shipment/sales schedules,

ensuring that product is available to meet market demand even if production is intermittent or batch-based.

- **Strategic Inventory:** Holding materials for reasons like speculative buying (anticipating price increases), seasonal demand, or as a contingency against supply chain disruptions.
- **Quality Control Hold-Up:** Providing necessary time for quality control analysis and certification before materials proceed to the next processing step or are released for shipment.
- **Safety and Containment:** Crucial for safely containing hazardous, flammable, toxic, or high-pressure materials, minimizing risks to personnel, property, and the environment.

2. Classification of Materials for Storage

The physical and chemical properties of the material are the primary drivers for selecting the appropriate storage method and equipment.

1. **Solids:**
    - **Bulk Solids:** Powders, granules, pellets, chips, lumps (e.g., catalysts, polymer pellets, coal, petroleum coke, fertilizers, aggregates). Their storage design is heavily influenced by flowability, dustiness, abrasiveness, and combustibility.
    - **Unit Loads:** Materials packaged in sacks, drums, bags, boxes, or Intermediate Bulk Containers (FIBCs). Stored in warehouses or dedicated storage areas.
2. **Liquids:** Vast range from highly viscous to very volatile, corrosive, or flammable. Stored in various types of tanks, designed to handle specific pressures and temperatures.
3. **Gases:** Stored under high pressure (gaseous state) or as liquefied gases (under pressure or cryogenically). Stored in specialized pressure vessels or cryogenic tanks.

3. Storage Equipment Types and Design Considerations

The selection and design of storage equipment are fundamental chemical engineering tasks, blending process requirements with safety, environmental, and economic considerations.

A. For Bulk Solids:

1. **Silos and Bins:**
    - **Description:** Vertical cylindrical or square structures, typically with conical or pyramidal bottoms, designed for the gravity discharge of bulk solids. Silos are generally larger.
    - **Chemical Engineering Design Considerations:**
        - **Flowability and Discharge:** Critical for preventing common issues like **arching** (material bridging over the outlet) and **rat-holing** (material flowing only through a narrow channel above the outlet). Designs promote either **mass flow** (all material moves when some is drawn out, preferred for sticky/cohesive materials to prevent stagnation and segregation) or **funnel flow** (only a central channel moves, suitable for free-flowing, non-segregating materials).
        - **Material Compatibility:** Selecting materials of construction (e.g., carbon steel, stainless steel, lined steel, concrete) that resist corrosion, abrasion, or contamination from the stored solid.
        - **Dust Control & Explosion Protection:** For combustible dusts (e.g., coal dust, polymer powders, some catalyst dusts), silos must be equipped with dust collection vents, explosion vents (rupture panels), and potentially inert gas blanketing (e.g., nitrogen purging) to prevent dust explosions.

        - **Segregation Prevention:** Design of filling (e.g., central loading with distributing devices) and discharge (e.g., mass flow) systems to minimize the separation of particles based on size or density during storage and retrieval.
        - **Level Monitoring:** Installation of continuous (e.g., radar, guided wave radar) or discrete (e.g., vibrating fork, capacitance) level sensors for inventory management and preventing overfilling/empty conditions.
        - **Temperature Control:** For heat-sensitive or reactive solids, temperature monitoring and cooling provisions (e.g., external cooling, inert gas purging) may be necessary.
    - **Applications in Refining/Chemicals:**
        - **Catalyst storage** (fresh and spent catalysts for FCC, hydrotreating, reforming units).
        - **Polymer pellets/powders** from polymerization units awaiting further processing or packaging.
        - **Coal** for power generation.
        - **Petroleum coke** (post-coking or post-calcination).
        - **Lime/limestone** for environmental control systems (e.g., flue gas desulfurization).
2. **Stockpiles (Outdoor):**
    - **Description:** Large, open-air piles of bulk solids, typically created and managed by mobile equipment (bulldozers, reclaimers).
    - **Chemical Engineering Design Considerations:**
        - **Environmental Exposure:** Susceptibility to rain, wind (dust generation), and temperature fluctuations.
        - **Spontaneous Combustion:** Critical for materials like coal and some types of coke, requiring careful pile management (compaction, temperature monitoring, fire suppression).

        - **Leaching:** Potential for undesirable substances to leach into the ground from rainfall.
        - **Dust Control:** Water sprays or chemical suppressants may be needed.
    - **Applications:**
        - Very large volumes of **coal** for power plants.
        - **Petroleum coke** (especially green coke).
        - **Solid sulfur** (often as blocks from solidification).
        - Aggregates used in construction related to plant expansion.
3. **Warehouses (for Bagged/Drummed Materials):**
    - **Description:** Enclosed buildings designed for the organized storage of unit loads (sacks, drums, barrels, FIBCs) on pallets or racks.
    - **Chemical Engineering Design Considerations:**
        - **Humidity Control:** For hygroscopic (moisture-absorbing) chemicals.
        - **Fire Suppression:** Appropriate fire detection and suppression systems (sprinklers, foam, inert gas) based on the flammability of stored materials.
        - **Ventilation:** For accidental leaks or fumes.
        - **Stacking and Segregation:** Proper stacking for stability, accessibility, and segregation of incompatible hazardous materials.
        - **Temperature Control:** For temperature-sensitive materials.
    - **Applications:**
        - **Bagged specialty chemicals, catalyst drums, barrels of additives, lubricants, packaged finished products.**

B. For Liquids:

Liquid storage tanks are ubiquitous in refineries and chemical plants, varying widely in design based on volatility, pressure,

temperature, and material properties. Compliance with industry standards like API 650 (Welded Tanks for Oil Storage) and API 620 (Large, Welded, Low-Pressure Storage Tanks) is paramount.

1. **Atmospheric Storage Tanks (Fixed Roof, Floating Roof):**
    - **Description:** Large, vertical cylindrical tanks designed for liquids stored at or near atmospheric pressure.
        - **Fixed-Roof Tanks:** Simplest, but have a large vapor space prone to evaporative losses and fire risk for volatile liquids. Often equipped with conservation vents and flame arrestors.
        - **Floating-Roof Tanks (Internal or External):** A roof that floats directly on the liquid surface, eliminating the vapor space. This significantly reduces evaporative losses, fire hazards, and emissions for volatile liquids.
    - **Chemical Engineering Design Considerations:**
        - **Vapor Pressure/Volatility:** Determines fixed vs. floating roof (floating roof for higher volatility, e.g., gasoline).
        - **Corrosion:** Material selection (carbon steel, stainless steel, special alloys, internal linings/coatings) based on liquid corrosivity.
        - **Thermal Expansion/Contraction:** Adequate venting to prevent overpressure or vacuum during temperature changes or filling/emptying.
        - **Overpressure/Vacuum Protection:** Safety relief valves (pressure/vacuum relief valves or breathers) are essential.
        - **Diking/Containment:** Secondary containment (e.g., concrete dikes, earthen berms) around tanks to contain spills and prevent environmental contamination.
        - **Fire Protection:** Foam systems, water deluge systems for cooling, fire monitors.

        - **Heating/Cooling Coils:** For viscous liquids (e.g., heavy fuel oil, asphalt, molten sulfur) that require heating to maintain fluidity, or for temperature-sensitive liquids requiring cooling.
    - **Applications: Crude oil, refined products (gasoline, diesel, jet fuel, fuel oil), intermediate hydrocarbons (naphtha, kerosene), solvents, process water, chemicals (acids, caustics).**
2. **Pressure Storage Vessels (Spheres, Horizontal Cylinders):**
    - **Description:** Designed to store liquids and gases under higher pressures than atmospheric tanks. Spheres are common for large volumes, while horizontal cylinders are used for smaller volumes.
    - **Chemical Engineering Design Considerations:**
        - **Pressure Rating:** Designed according to ASME boiler and pressure vessel code.
        - **Material Toughness:** Especially for materials stored at low temperatures (e.g., ammonia).
        - **Thermal Expansion:** Accounting for volumetric changes.
        - **Safety Relief:** Pressure relief valves are critical.
    - **Applications: Liquefied Petroleum Gas (LPG - propane, butane), naphtha, anhydrous ammonia, light hydrocarbons.**
3. **Cryogenic Storage Tanks:**
    - **Description:** Double-walled, vacuum-insulated tanks designed to store gases as super-cooled liquids at very low (cryogenic) temperatures.
    - **Chemical Engineering Design Considerations:**
        - **Extreme Insulation:** Vacuum between walls, often with perlite or multi-layer insulation, to minimize heat transfer.
        - **Material Properties:** Materials of construction must maintain mechanical integrity at cryogenic

temperatures (e.g., stainless steel, specific aluminum alloys).
        - **Boil-Off Gas Management:** Systems to manage and recover vaporized product (boil-off gas) due to unavoidable heat ingress.
        - **Safety Relief:** Specialized pressure relief devices for extremely low temperatures.
    - **Applications: Liquefied Natural Gas (LNG), ethylene, propylene, liquid oxygen, liquid nitrogen, liquid hydrogen.**

C. For Gases (Pressurized):

1. **Pressure Vessels/Gas Cylinders:**
    - **Description:** High-pressure steel containers ranging from small gas cylinders to large spherical or bullet-shaped vessels.
    - **Chemical Engineering Design Considerations:**
        - **Design Codes:** Compliance with national and international pressure vessel codes (e.g., ASME, EN).
        - **Pressure Rating:** Determined by the gas pressure.
        - **Material of Construction:** Chosen for strength and compatibility with the gas.
        - **Safety Relief Devices:** Pressure relief valves, rupture discs are mandatory.
        - **Regular Inspection:** Periodic hydrostatic testing and visual inspections.
    - **Applications: Hydrogen, natural gas, nitrogen, oxygen, various industrial gases used as utilities or reactants.**

6. Chemical Engineering Operational & Safety Considerations

Beyond equipment design, operational practices and safety protocols are paramount for storage systems.

1. **Inventory Management:**
    - **Accurate Level Monitoring:** Using various technologies (radar, servo, float gauges) for real-time inventory tracking.
    - **Inventory Tracking Systems:** Integration with Enterprise Resource Planning (ERP) systems for efficient supply chain management.
    - **Optimal Inventory Levels:** Balancing the cost of holding inventory (capital tie-up, operating costs) against the risk of stock-outs or market fluctuations.
2. **Safety (Overriding Principle):**
    - **Fire & Explosion Prevention:**
        - **Vents and Flame Arrestors:** For atmospheric tanks to allow breathing while preventing flame propagation.
        - **Inerting/Blanketing:** Using nitrogen to maintain an oxygen-deficient atmosphere in the vapor space of tanks holding flammable liquids or combustible powders, preventing explosions.
        - **Cooling Systems:** For tanks exposed to external fires (deluge systems).
        - **Fire Suppression Systems:** Foam systems for liquid hydrocarbons, inert gas for warehouses.
        - **Grounding and Bonding:** Preventing static electricity buildup during transfer, a common ignition source.
    - **Vapor Emission Control:** Implementing vapor recovery units (VRUs) for highly volatile organic compounds (VOCs) to meet environmental regulations and recover valuable product. Floating roofs are a passive method.
    - **Toxic Material Containment:** Double-walled tanks, secondary containment (diking), leak detection systems, and robust emergency response plans.

- **Overpressure/Vacuum Protection:** Redundant pressure relief valves and rupture discs to protect tanks and vessels from catastrophic failure.
- **Spill Containment:** Diking around liquid storage tanks, spill kits, and drainage systems directed to treatment.
- **Emergency Response:** Clearly defined procedures for leaks, fires, explosions, and other incidents, including personnel training.

3. **Product Quality Preservation:**
   - **Contamination Prevention:** Dedicated storage tanks and transfer lines for different products, rigorous cleaning procedures, inert gas blanketing.
   - **Degradation Prevention:** Temperature control (heating/cooling), inert blanketing for oxygen-sensitive materials (e.g., monomers), protection from UV light.
   - **Moisture Absorption:** Dry air blanketing for hygroscopic solids or liquids.
   - **Segregation:** Proper design of solids storage to prevent particle separation.
4. **Maintenance & Inspection:**
   - **Regular Inspections:** Compliance with industry standards (e.g., API 653 for in-service tank inspection).
   - **Corrosion Monitoring:** Internal and external inspection, cathodic protection.
   - **Cleaning:** Periodic cleaning of tanks and silos to remove sludge, scale, or product residues.
5. **Environmental Compliance:** Adherence to regulations regarding emissions, waste disposal from tank cleaning, and spill prevention.

7. Relevance to Petroleum Refining and Petrochemicals

Storage facilities are an indispensable part of every refinery and petrochemical complex:

- **Crude Oil Storage:** Large tank farms for receiving and storing various crude oil grades before processing.
- **Refined Products Storage:** Extensive tankage for finished products like gasoline, diesel, jet fuel, fuel oil, lubricants, and asphalt awaiting distribution.
- **Intermediate Hydrocarbon Storage:** Tanks for naphtha, kerosene, gas oil, and various reformate/cracked streams that act as feedstocks for downstream units or blending components.
- **Petrochemical Feedstock and Product Storage:** Specialized tanks for light hydrocarbons (ethylene, propylene, butadiene, benzene, toluene, xylene), often under pressure or cryogenic conditions.
- **Chemicals and Additives:** Storage for acids, caustics, various process chemicals, catalyst inventories, and polymer additives.
- **Utility Storage:** Tanks and vessels for fuel gas, process water, fire water, inert gases (nitrogen), and oxygen.
- **Sulfur Storage:** Liquid sulfur in heated tanks from the Sulfur Recovery Unit (SRU) or solid sulfur stockpiles.

4/ Posttest

- Define storage and explain two of its primary functions in an industrial setting.
- What is the main difference between static and dynamic storage?
- Name two types of storage equipment used for bulk solids and two for unit loads.
- List three important considerations when designing a storage area.

5/ Homework

- Research a "First-In, First-Out (FIFO)" vs. "Last-In, First-Out (LIFO)" storage strategy. Explain when each might be preferred.
- Visit a local supermarket or a small warehouse (if possible, or watch a video) and identify at least three different storage methods they use.

6/ References

- "Supply Chain Management: Strategy, Planning, and Operation" by Sunil Chopra and Peter Meindl.
- "Warehouse Management: A Complete Guide to Improving Efficiency and Minimizing Costs" by Gwynne Richards.
- "Logistics & Supply Chain Management" by Martin Christopher.
- Industry best practices and guidelines from material handling associations.