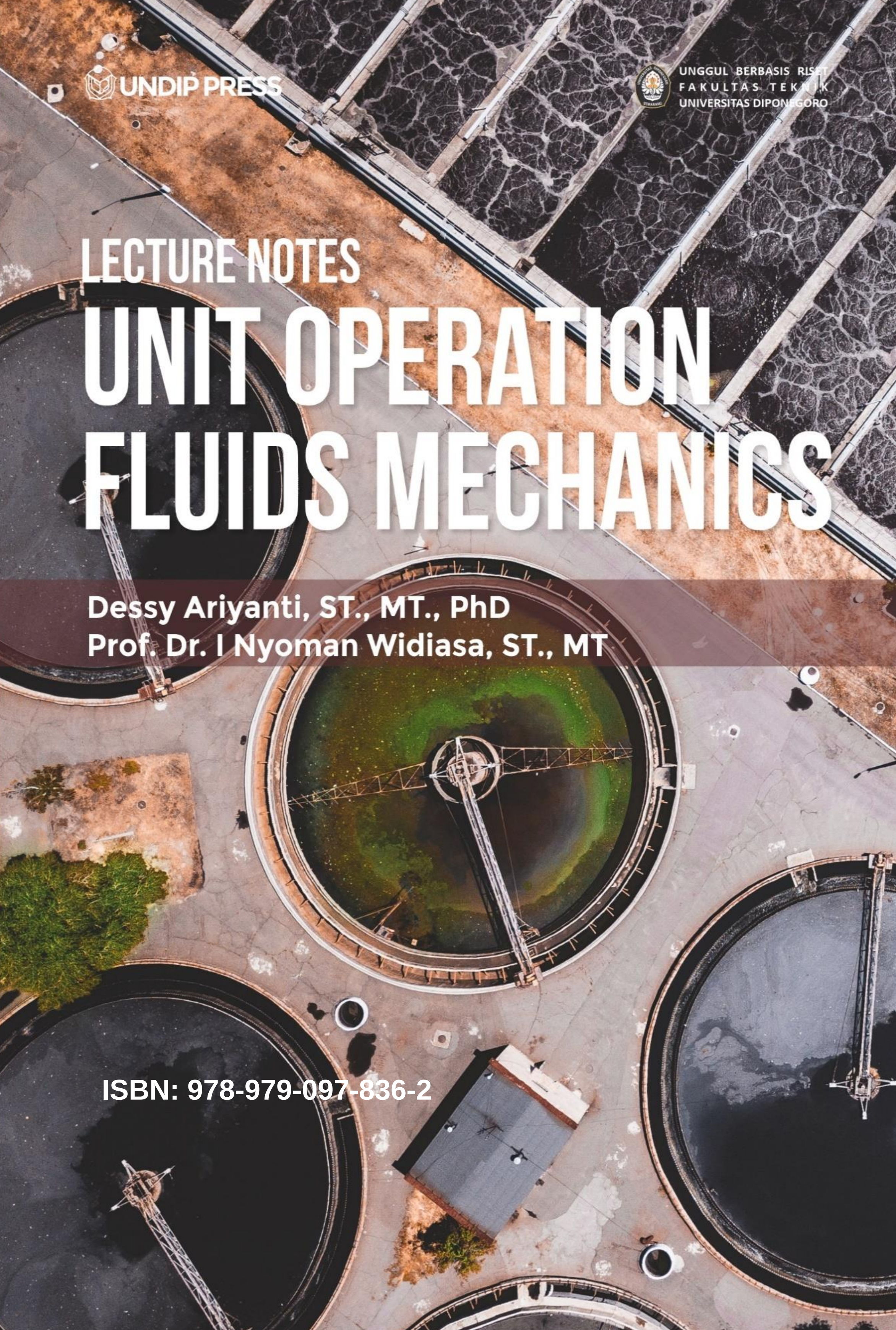

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LECTURE NOTES

UNIT OPERATION FLUIDS MECHANICS

Dessy Ariyanti, ST., MT., PhD
Prof. Dr. I Nyoman Widiasa, ST., MT

ISBN: 978-979-097-836-2

LECTURE NOTES

UNIT OPERATION 2: FLUIDS MECHANICS

Course : Unit Operation 2: Fluids Mechanics
Study Program : Chemical Engineering
Faculty : Engineering

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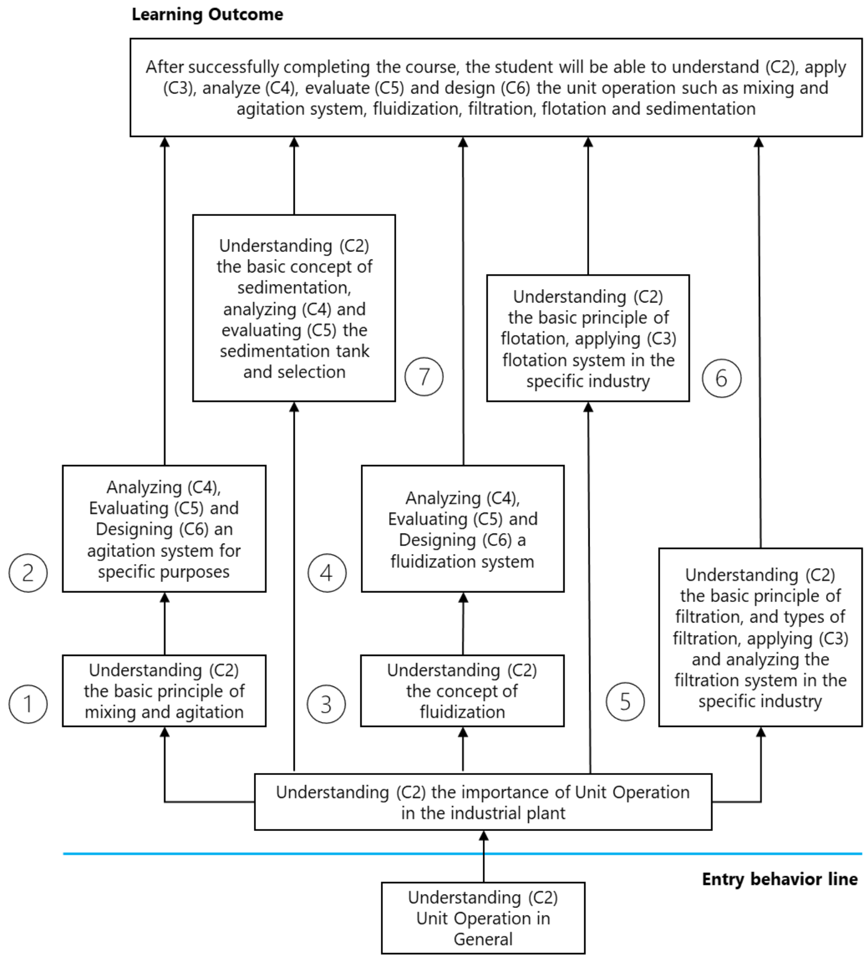
This book is dedicated to IUP students at Department of Chemical Engineering, Faculty of Engineering, Universitas Diponegoro

LEARNING ANALYSIS

Course : UNIT OPERATION 2: FLUIDS MECHANICS
Code : TKM21228
Credits : 3 SKS



PREFACE

Chemical engineering unit operations is the main principles and important aspect in the designs of chemical plants and industries. Unit operation is a basic step in a process that involve a physical change or chemical transformation such as separation, crystallization, evaporation, filtration, and other reactions. In the Department of Chemical Engineering, Faculty of Engineering, Universitas Diponegoro, the Unit Operation were divided into four parts namely, Unit Operation 1: Mechanical Process; Unit Operation 2: Fluids Mechanics; and Unit Operation 3: Heat Separation; and Unit Operation 4: Multistage separation. Unit Operation 2: Fluids Mechanics were delivered for students' year three so that after completing the course they will be able to design the unit operation involving fluids mechanics such as mixing and agitation, fluidization, filtration, floatation, and sedimentation.

In the preparation of this teaching notes, the authors used many references and literatures as well as materials from books, internet source and journal papers that aims to expanding the perspective of the discussions subject. The authors thank everyone who contributed to the preparations of this lecture notes. The authors also emphasized that this note is used for teaching purpose only and not for commercial.

Semarang, September 4th, 2021

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COURSE OVERVIEW

I. Description

Unit Operation 2: Fluids Mechanics explained the basic principles of several fluids mechanics-based unit operation system such as mixing and agitation, fluidization, filtration, floatation, and sedimentation that commonly used in the industrial plant. That's include the types that are available and the selection process for particular needs as well as parameters involved in the process along with the designing calculations and study cases.

II. Relevance

Chemical engineering unit operations is the main principles and important aspect in the designs of chemical plants and industries. This course will give students knowledge on the understanding, application and designing process of fluids mechanics-based unit operations for further application in the designing new plants for conducting new processes.

III. Learning Outcome

After completing the course students will be able to design (C6) chemical engineering operations units including a complex integrated system consisting of several operating units. In details, students will be able to:

a) explain (C2) the basic concepts of agitation, a type of agitation type

b) Analyse (C4) and select the type of agitation as well as design (C6) an agitation system for particular process.
c) Explain (C2) the concept of fluidization and the phenomenon of fluidization, the parameters in fluidization and the use of fluidization in the industry.
d) Analyse (C4), evaluate (C5) and design (C6) the fluidization system.
e) Explain (C2) the basic concepts of the filtration process and apply (C3) specific type of filtration for particular system.
f) explain (C2) the principles of flotation, application (C3), and flotation process system
g) Explain (C2) the basic concepts and principles of the sedimentation process and analyse and evaluate (C4, C5) the design sedimentation tank.

IV. Learning Indicators

The successful completion of the course is indicated by minimum 60% achievement of the learning outcome which will be measured through quizzes, case study discussions, group assignment, and exam.

CHAPTER 1

MIXING AND AGITATION

1. Introduction

1.1 Brief Description

This chapter discussed the definition of agitators and mixing in general, agitation equipment, agitator selection and design calculation.

1.2 Relevance

Chemical engineering unit operations is the main principles and important aspect in the designs of chemical plants and industries especially mixing and agitation system that can be found in almost 90% in industries. The ability to understand the system needed and to design an agitation system for specific purposes is necessary for the students.

1.3 Learning Outcome

After completing the course students will be able to design (C6) chemical engineering operations units including a complex integrated system consisting of several operating units. In details, students will be able to:

a) explain (C2) the basic concepts of agitation,

b) explain (C2) various type of agitation

c) analyse (C4) and select the type of agitation

d) design (C6) an agitation system for particular process.

1.4 Learning Instruction

Read the Chapter 1 along with other complementary supplements such as Unit Operation by Brown, 1950. Work on the exercise and quizzes for improve the learning outcome achievements.

2. Materials

2.1 Materials Description

Definition

Mixing and agitation are the action in reducing inhomogeneity by applying mechanical forces. Almost 99% of process industries applied mixing and agitation as important part of the process (influence the reaction rate, yield and product consistency).

Objectives of mixing and agitation:

1. Mass transfer in heterogeneous systems (chemical reaction, solution of solid, extraction, absorption, and adsorption)
2. Mixing or blending of two liquids
3. Physical change or emulsification (emulsification of two immiscible liquid)
4. Heat transfer (uniformity of temperature)

Mixing combinations in general can be seen in Figure 1.1.

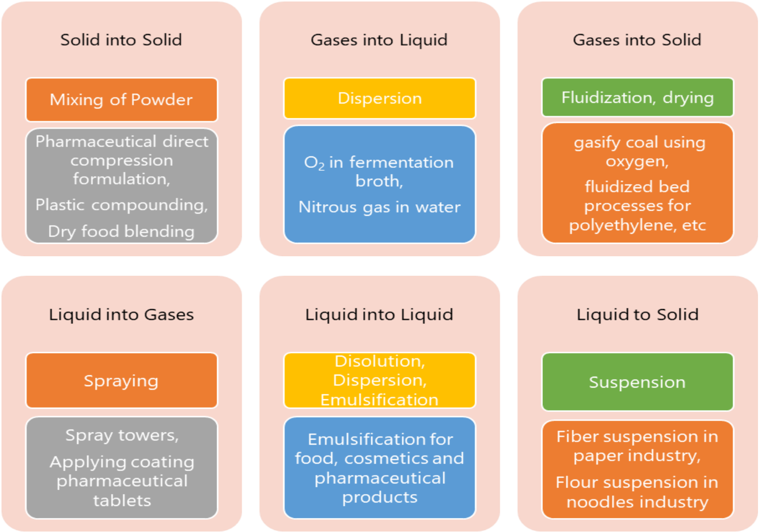
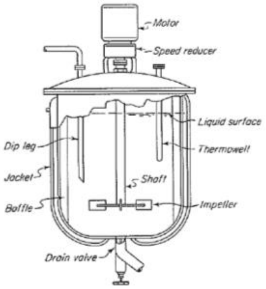


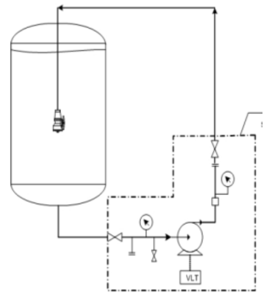
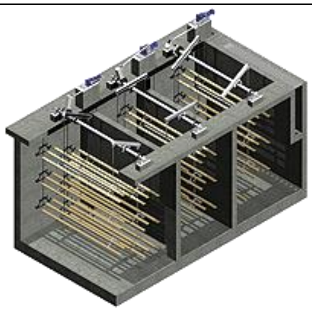
Figure 1.1 Various mixing combination and the application

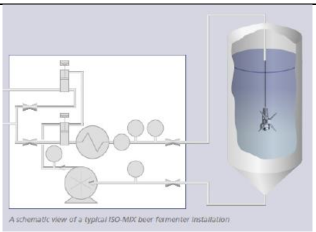
Agitation equipment

There are many agitations equipment available, and it can be divided into seven types according to Table 1.1.

Table 1.1. Various agitations equipment

Type	**Schematic Draw**	**Remark**
Rotating impellers		Vessels (conical, hemispherical, rectangular, cylindrical); Baffles; Impellers

Type	Schematic Draw	Remark
Circulating Pump Systems		Vessels (conical, hemispherical, rectangular, cylindrical); Centrifugal pump
Reciprocating Paddles		Rectangular Tanks; Paddle / blade (moved back and forth through the tank)
Revolving Tanks or Pans		Double conical or cylindrical tanks; Static Paddle / blade; Sprayer
Air Lift and Air Agitators		Tanks; Large diameter tube

Type	Schematic Draw	Remark
Mixing Jet		Cylindrical tank; Nozzles
Static/Inline mixing		Pipe; Turbulence promoters, (orifices or baffles); Centrifugal pumps

Agitator selection

Steps for agitator selection:

1. Find out the objectives and requirements of the process
2. Analyse the phases involved in the process

For solid and paste materials as shown in Table 1.2. and Table 1.3: Most solid and paste mixers are designed for batch operation. In the mixing of solid particles, the following three mechanisms may be involved:

1. Convective mixing, in which groups of particles are moved from one position to another,
2. Diffusion mixing, where the particles are distributed over a freshly developed interface, and
3. Shear mixing, where slipping planes are formed.

A trough mixer with a ribbon spiral involves almost pure convective mixing, and a simple barrel-mixer involves mainly a form of diffusion mixing.

Table 1.2. Various types of solid-paste agitators

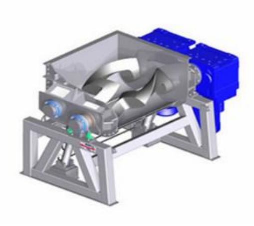
Characteristics of feed	Type of agitator	Schematic drawing
free-flowing solids	Cone blenders	
dry solids and for blending liquids with solids	Ribbon blenders	
heavy pastes	Z-blade mixers and pan mixers	

Table 1.3. Various types of solid-paste agitators with application

Type of equipment	Mixing action	Application	Examples
Rotating: cone, double cone, drum	Tumbling action	Blending dry, free flowing powders, granules, crystals	Pharmaceuticals, food, chemicals
Air blast fluidisation	Air blast lifts and mixes particles	Dry powders and granules	Milk powder; detergents, chemicals
Horizontal trough mixer, with ribbon blades, paddles or beaters	Rotating element products contra-flow movement of materials	Dry and moist powders	Chemicals, food, pigments, tablet granulation
Z-blade mixers	Shearing and kneading by the specially shaped blades	Mixing heavy pastes, creams, and doughs	Bakery industry, rubber doughs, plastic dispersions
Pan mixers	Vertical, rotating paddles, often with planetary motion	Mixing, whipping and kneading of the materials ranging from low viscosity pastes to stiff doughs	Food, pharmaceuticals and chemicals, printing inks and ceramics
Cylinder mixers, single and double	Shearing and kneading action	Compounding of rubbers and plastics	Rubbers, plastics and pigment dispersion

For gas mixing, specialized equipment is seldom needed as it has low viscosities that can be mixed easily. The mixing given by turbulent flow in a length of pipe is usually sufficient for most purposes. Turbulence promoters, such as orifices or baffles, can be used to increase the rate of mixing.

For liquid mixing, there are several factors in choosing equipment for mixing liquids:

1. Batch of continuous operation.
2. Nature of the process: miscible liquids, preparation of solutions, or dispersion of immiscible liquids.
3. Degree of mixing required.
4. Physical properties of the liquids, particularly the viscosity.
5. Whether the mixing is associated with other operations: reaction, heat transfer.

For the continuous mixing of low viscosity fluids inline mixers can be used. For other mixing operations stirred vessels or proprietary mixing equipment will be required. In stirred vessel the impeller selection become important. Impeller selection should be based on:

1. type of mixing required,
2. the capacity of the vessel,
3. and the fluid properties, mainly the viscosity

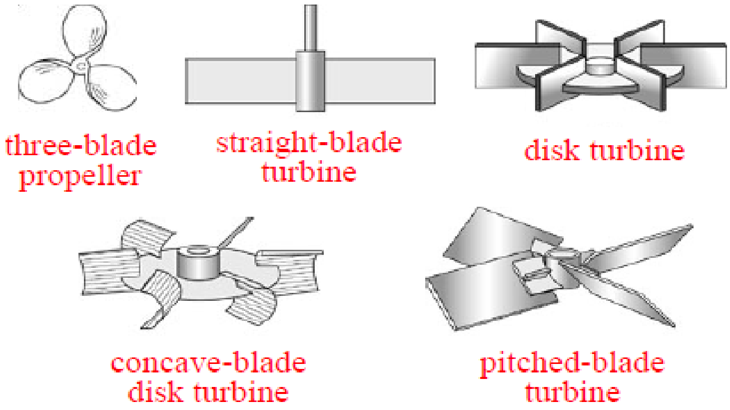


Figure 1.2 High Re number-low viscosity fluids impellers

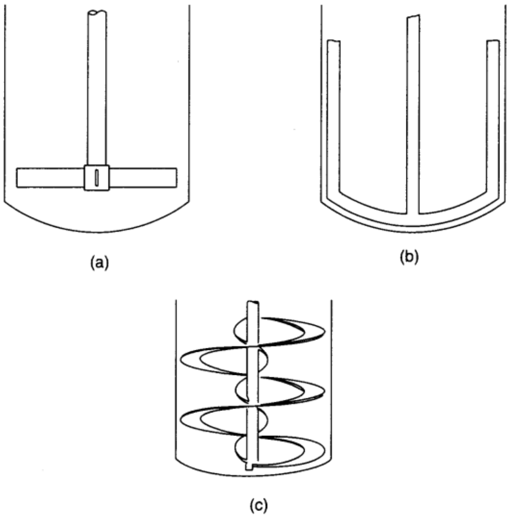


Figure 1.3 Low Re number-viscous fluid impellers (a) Paddle; (b) Anchor; (c) Helical ribbon

In order to select a suitable impeller for particular process, there are two parameters for considerations:

1. Liquid viscosity
2. Tank Volume

The value of liquid viscosity and tank volume then placed in the Figure 1.4 for selection.

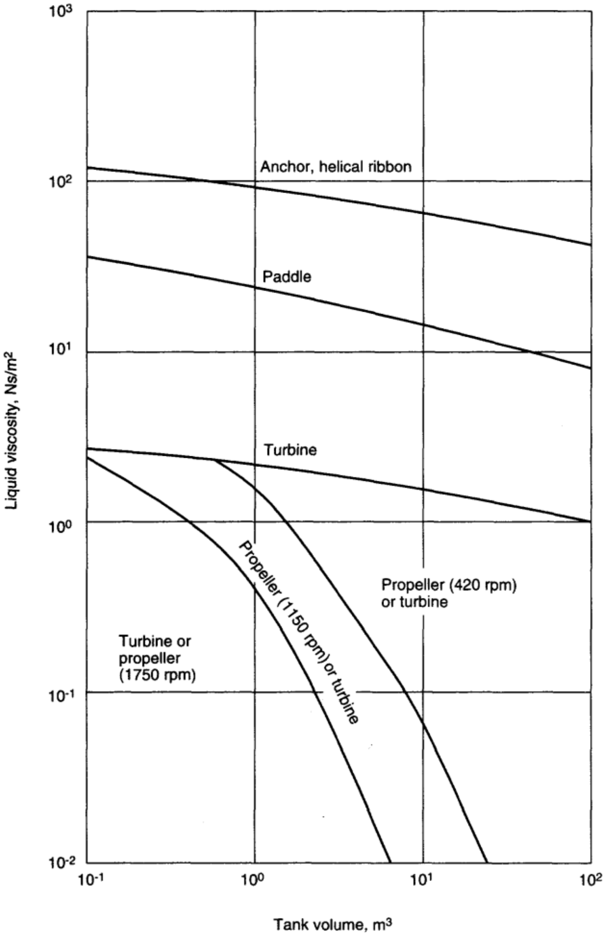
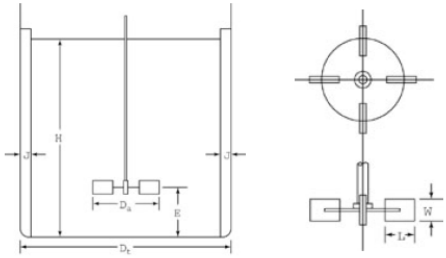


Figure 1.4 Agitator selection guide

Standard turbine design



H : depth of liquid

D_t : tank diameter

D_a : impeller diameter

L : blade length

W : impeller width

J : width of baffle

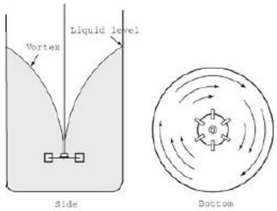
E : clearance

Typical proportions:

$$\frac{D_a}{D_t} = \frac{1}{3} \quad \frac{H}{D_t} = 1 \quad \frac{J}{D_t} = \frac{1}{12} \quad \frac{E}{D_t} = \frac{1}{3} \quad \frac{W}{D_a} = \frac{1}{5} \quad \frac{L}{D_a} = \frac{1}{4}$$

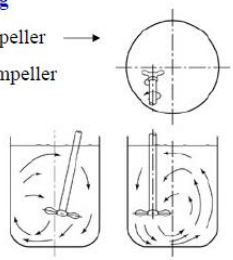
& No. of baffles: 4, No. of impeller blades: 6 or 8

Swirling flow pattern



Prevention of swirling

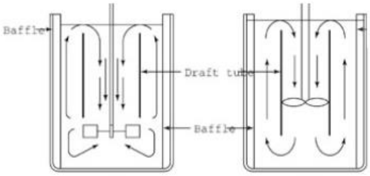
- off-centered impeller →
- side-mounted impeller
- baffles



Draft tubes

Controls direction and velocity of flow

Useful when high shear is desired such as emulsions and suspensions



turbine propeller

Draft tubes, baffled tank

Power consumption in agitated vessel

An important consideration in the design of an agitated vessel is the power required to drive the impeller. To estimate the power required, an empirical correlations of power number with the other variables of the system are needed.

Dimensionless groups:

$$N_{RE} = \frac{nD_a^{\,2}\rho}{\mu}$$

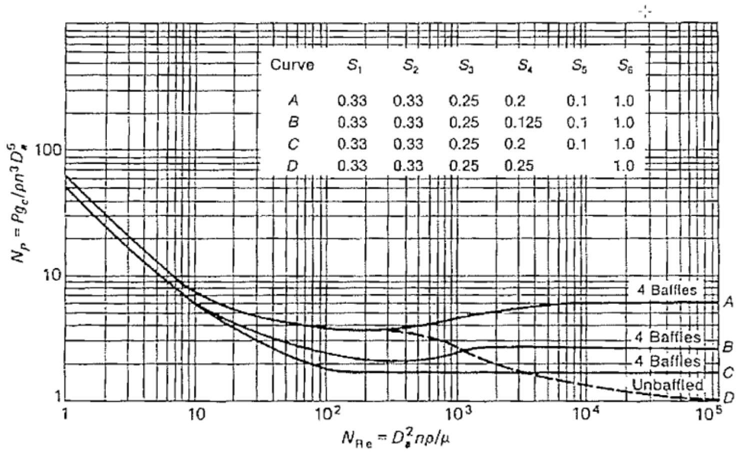
$$N_{FR} = \frac{nD_a^{\,2}}{g_c}$$

$$N_P = \frac{Pg_c}{n^3 D_a^{\,5}\rho}$$

N_{RE} = Reynold number
N_{FR} = Froude number
N_P = power number
n = speed of impeller
D_a = impeller diameter
g_c = gravitational acc.
ρ = fluid density
μ = viscocity

Power correlations for specific impellers

The various shape factors in the equation depend on the type and arrangement of the equipment. The necessary measurements for a typical turbine-agitated vessel are shown in Figure… the corresponding shape factors for this mixer are S1 = Da / Dt ; S2 = E / Da; S3 = L / Da; S4 = W / Dt; S5 = J / Dt; S6 = H / Dt. In addition, the number of baffles and the number of the impeller's blades must be specified.



Curve A applies for vertical blades with S4 = 0.2; Curve B applies to similar impeller with narrower blades (S4 = 0.125); Curve C is for pitched-bladed turbine; Curve D for unbaffled tank

Figure 1.5 Power number Np versus N_{RE} for six blade turbines

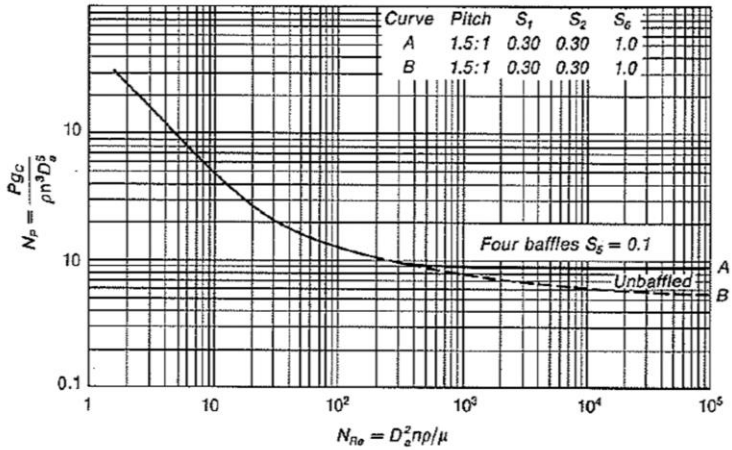


Figure 1.6 Power number Np versus N_{RE} for three blade turbines

Calculation of power consumption according to Mc Cabe, et al. 1993 can be used for N_{RE} value less than 10, as if the flow is laminar then the density will no longer be a factor.

$$P = \frac{N_p n^3 D_a^5 \rho}{g_c}$$

At low Reynold numbers

$$N_P = \frac{K_L}{N_{RE}}$$

Which make:

$$P = \frac{K_L n^2 D_a^3 \mu}{g_c}$$

In tanks with baffle at N_{RE} larger than 10,000, the power will be independent, and the viscosity will not be a factor:

$$N_P = K_T$$

Which make:

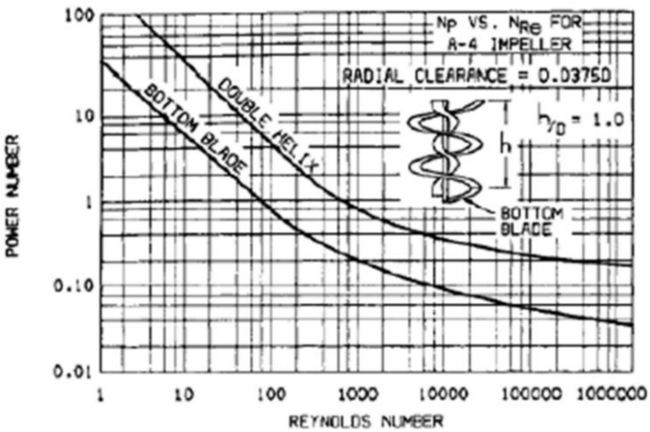
$$P = \frac{K_T n^2 D_a^3 \mu}{g_c}$$

The value of the constant K_T and K_L for various type of impellers and tanks can be seen in Table 1.4.

Table 1.4 value of the constant KT and KL for baffled tanks with four baffles and with equal to 10 percent of the tank diameter

Type of Impeller	**K_L**	**K_T**
Propeller, three blades		
Pitch 1.0	41	0.32
Pitch 1.5	55	0.87
Turbine		
Six blade disks (S_3 =0,25, S_4 = 0,2)	65	5.75
Six curved blades (S_4 = 0,2)	70	4.80
Six pitched blades (45^o S_4 = 0,2)	-	1.63
Four pitched blades (45^o S_4 = 0,2)	44.5	1.27
Flat paddle, two blades (S_4 = 0,2)	36.5	1.70
Anchor	300	0.35

Type	No. baffles	N_p	N_Q
Propeller	0	0.3	
Propeller	3–8	0.33–0.37	0.40–0.55
Turbine, vertical blade	0	0.93–1.08	0.33–0.34
Turbine, vertical blade	4	3–5	0.70–0.85
Pitched turbine, 45°	0	0.7	0.3
Pitched turbine, 45°	4	1.30–1.40	0.60–0.87
Anchor	0	0.28	



(a)

Figure 1.7 Power number Np versus N_{RE} for helical shape

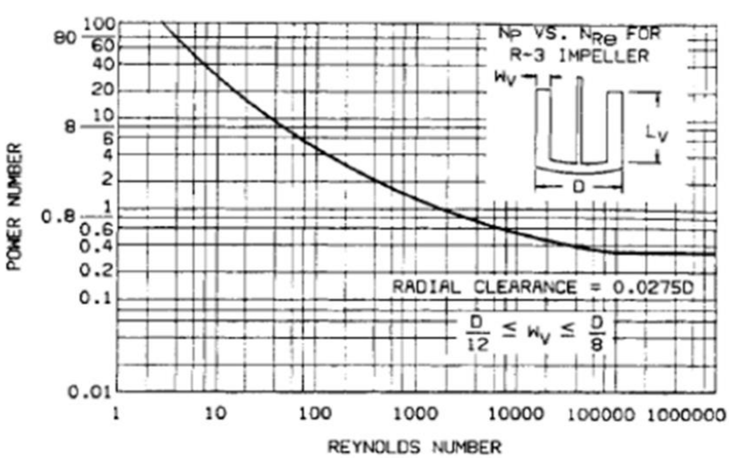
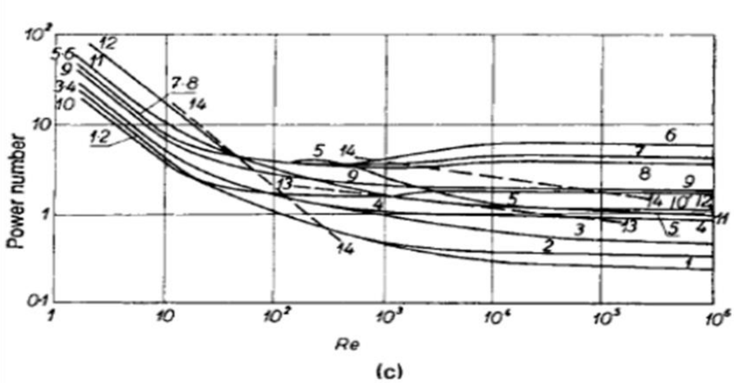


Figure 1.8 Power number Np versus N_{RE} for anchor shape



(1) propeller, pitch equalling diameter, without baffles; (2) propeller, s =d, four baffles; (3) propeller, s =2d, without baffles; (4) propeller, s =2d, four baffles; (5) turbine impeller, six straight blades, without baffles; (6) turbine impeller, six blades, four baffles; (7) turbine impeller, six curved blades, four baffles; (8) arrowhead turbine, four baffles; (9) turbine impeller, nclined curved blades, four baffles; (10) two-blade paddle, four baffles; (11) turbine impeller, six blades, four baffles; (12) turbine impeller with stator ring; (13) paddle without baffles (data of Miller and Mann); (14) paddle without baffles (data of White and Summerford). All baffles are of width 0.1D [afterRushton, Costich, and Everett, Chem. Eng. Prog. 46(9), 467 (1950)l

Figure 1.9 Power number Np versus N_{RE} for various type of impellers

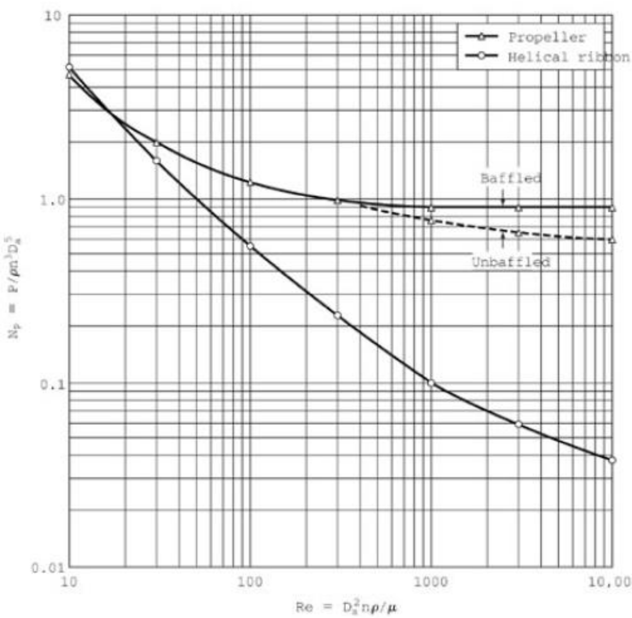


Figure 1.10 Power number Np versus N_{RE} for propellers and helical ribbons

2.2 Exercise

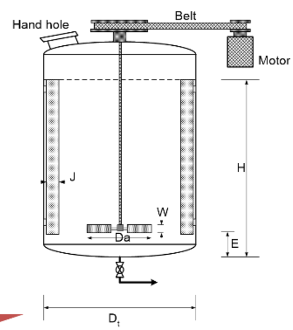
Stirring emulsion system is designed to use 2 leaves paddle propeller mounted vertically in the center of the tank. Tank diameter (Dt) 10 ft., tank height 12 ft., mixer diameter (Da) 3 ft., mixer position (E) 1 meter above the tank base, with a spin (n) 120 rpm. The operation takes place at room temperature. The height of the solution (H) is 10 Ft., the density of the solution type (() 1.66 g/ml and viscosity (μ) 32 cp. Calculate the stirring power needed when the thickness of a 4-piece baffle tank is 1 ft.?

3. End of Chapter 1

3.1 Summary

Variables that affect the power of the agitator are:

- Agitator properties: n, Da, W, L
- Properties of liquid: μ, ρ
- Gravitational acceleration: g
- Geometry factors : H, E, J, Dt

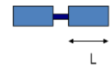


S_1 = Da / Dt **S_2 = E / Da** **S_3 = L / Da**
S_4 = W / Dt **S_5 = J / Dt** **S_6 = H / Dt**

$N_{Re} = n.Da^2.\rho/\mu$

$$P = \frac{N_P . n^3 . Da^5 \rho}{g_c}$$

The installed motor power is able to handle the process according to the range of operating conditions: T min and max concentration.



3.2 Exam

A flat-blade turbine with six blades is installed centrally in a vertical tank. The tank is 6 ft. (1.83 m) in diameter; the turbine is 2 ft. (0.61 m) in diameter and is positioned 2 ft. (0.61 m) from the bottom of the tank. The turbine blades are 5 in. (127 mm) wide. The tank is filled to a depth of 6 ft (1.83 m) with a solution of 50% caustic soda, at 150°F (65.6°C), which has a viscosity of 12 cP and a density of 93.5 lb/ft^3 (1498 kg/m^3). The turbine is operated at 90r/min. The tank is baffled. What power will be required to operate the mixer?

3.3 Feedback

Successful completion of this chapter is measured by the ability of students to explain the basic concepts of agitation, a type of agitation type, analyse and select the type of agitation as well as design an agitation system for particular process.

3.4 Following action

Students can practice solving the mixing and agitation problem which are available in reference book. After that, students can continue to read the following chapters.

3.5 Solution

Curve A in Figure 1.4 can be used as a tool for solving the problems. First listed the variables that has value or number. The Reynold number is calculated

$$D_a = 2\,ft \qquad n = \frac{90}{60} = 1.5\,r/s$$

$$\mu = 12 \times 6.72 \times 10^{-4} = 8.06 \times \frac{10^{-3} lb}{ft\,s}$$

$$\rho = \frac{93.5 lb}{ft^3} \qquad g = 32.17 \frac{ft}{s^2}$$

Then

$$N_{RE} = \frac{D_a n\rho}{\mu} = \frac{2^2 \times 1.5 \times 93.5}{8.06 \times 10^{-3}} = 69{,}600$$

From curve A (Figure 1.4) for N_{RE} = 69,600, N_P = 5.8, and the power can be calculated:

$$P = \frac{5.8 \times 93.5 \times 1.5^3 \times 2^5}{32.17} = 1821\ ft - lbf/s$$

The power requirement is 1821/550 = 3.31 hp (2.47kW)

References

1. Warren L. McCabe, Julian C. Smith, Peter Harriott., 1993. Unit Operations of Chemical Engineering, 5th Edition, Singapore: McGraw-Hill.
2. Brown, G.G., Kate, D., Foust, A.S., and Schneidewind, R. 1950. Unit Operations. New York: Jhon Wiley & Sons, Inc.
3. Green, D.W. and Maloney, J.O. 1997. Perry's Chemical Engineers Handbook. USA: Mc Graw Hill Ltd.

Glossary

Reynolds Number (N_{RE}) ratio of inertial forces to viscous forces within a fluid which is subjected to relative internal movement due to different fluid velocities.

Froude number (N_{Fr}) is a dimensionless number defined as the ratio of the flow inertia to the external field (the latter in many applications simply due to gravity).

CHAPTER 2
FLUIDIZATION

1. Introduction

1.1 Brief Description

This chapter discussed about fluidization application, basic principles of fluidization, Geldart's classic classification of powders, type of fluidization and fluidization design calculation.

1.2 Relevance

The fluidization concept holds many applications in reactor, dryer as well as particle transportation. The ability to understand the system needed and to design an fluidization system for specific purposes is necessary for the students.

1.3 Learning Outcome

After completing the course students will be able to design (C6) chemical engineering operations units including a complex integrated system consisting of several operating units. In details, students will be able to:

a) explain (C2) the concept of fluidization and the phenomenon of fluidization,

b) explain (C2) the parameters in fluidization and the use of fluidization in the industry.

c) Analyse (C4), evaluate (C5) and design (C6) the fluidization system.

1.4 Learning Instruction

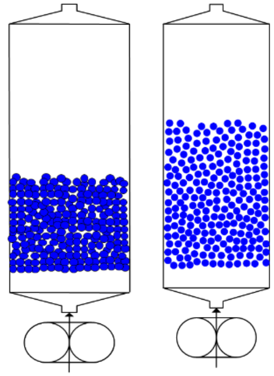
Read the Chapter 2 along with other complementary supplements such as, Unit Operations of Chemical Engineering, by Mc Cabe et al 1993 and Unit Operation by Brown, 1950. Work on the exercise and quizzes for improve the learning outcome achievements.

2. Materials

2.1.a Materials Description

Fluidization is a process whereby a granular material is converted from a static solid-like state to a dynamic fluid-like state. This process occurs when a fluid (liquid or gas) is passed up through the granular material. When a gas flow is introduced through the bottom of a bed of solid particles, it will move upwards through the bed via the empty spaces between the particles. At low gas velocities, aerodynamic drag on each particle is also low, and thus the bed remains in a fixed state.

Increasing the velocity, the aerodynamic drag forces will begin to counteract the gravitational forces, causing the bed to expand in volume as the particles move away from each other. Further increasing the velocity, it will reach a critical value at which the upward drag forces will exactly equal the downward gravitational



orces, causing the particles to become suspended within the fluid. At this critical value, the bed is said to be fluidized and will exhibit fluidic behaviour. By further increasing gas velocity, the bulk density of the bed will continue to decrease, and its fluidization becomes more violent, until the particles no longer form a bed and are "conveyed" upwards by the gas flow.

Fluidization application

Chemical Engineering unit operation that applied fluidization concept:

- Reactor (fluidized bed reactor)
- Dryer (fluidized bed dryer)
- Particle transportation

Example:

- dimethyl-benzene amoxidation to IPN two stage turbulent fluidized bed reactor (500 ton/a) 2 unit

- Naphthalene oxidation to phenyl acetate turbulent fluidized bed reactor (20 KT/a) 10 unit
- HCl and acetylene to vinyl C_2H_3Cl multistage fluidized bed reactor (3 KT/a,100KT/a) 3 unit

Figure 2.1 Various fluidization application the industry

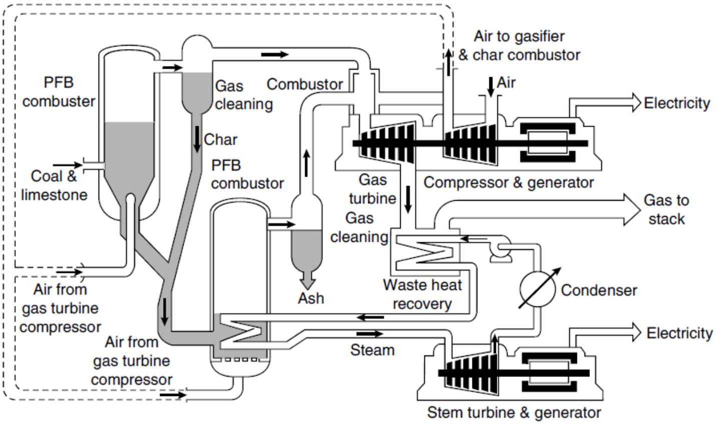


Figure 2.2 Pressurized fluidised bed combustor with waste heat recovery

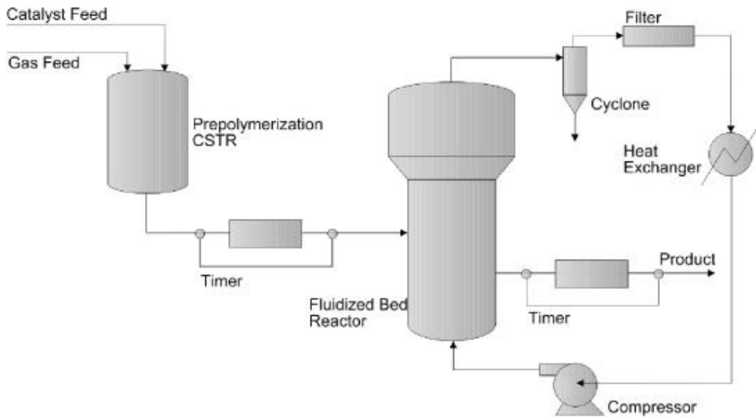


Figure 2.3 Diagram of industrial polyethylene production (BP Chemical Technology)

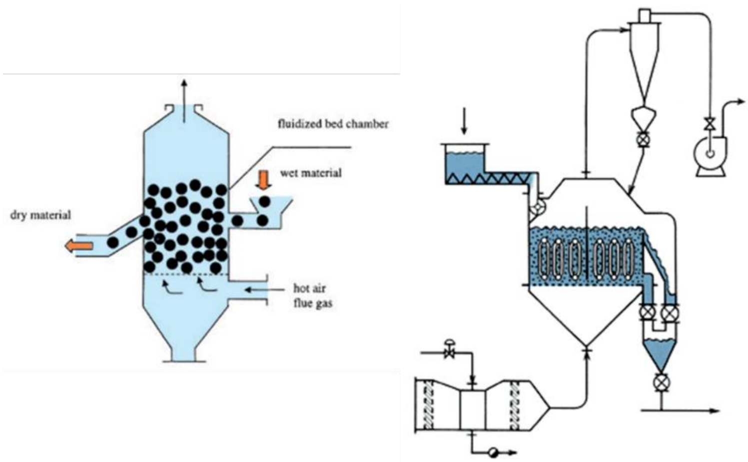


Figure 2.4 Diagram of industrial Fluidized Bed Dryer

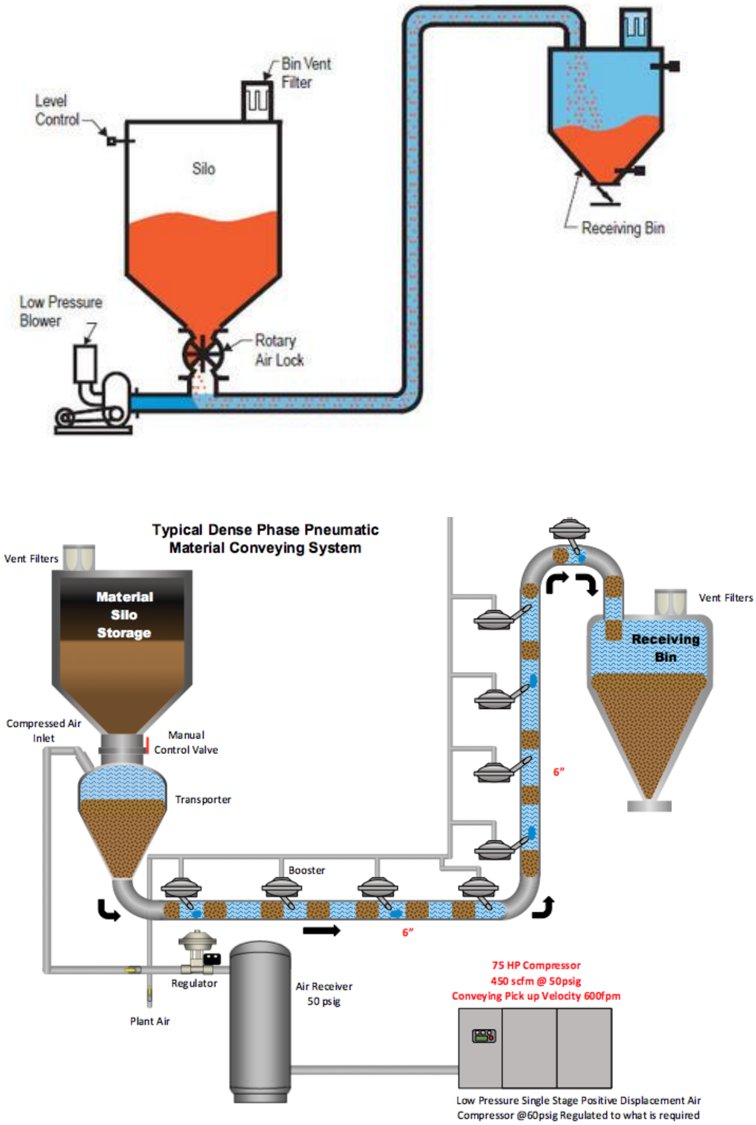


Figure 2.5 Schematic of particle transportation pneumatic conveyor

Basic principles of fluidisation

When a gas flow is introduced through the bottom of a bed of solid particles, the pressure drop occurred due to resistance of the solid particles following the Ergun equation:

$$\frac{\Delta P.g_c}{L}\frac{\phi_S.D_P\varepsilon^3}{\rho.V_o^2(1-\varepsilon)} = \frac{150.(1-\varepsilon)}{\phi_S.D_P V_o.\rho/\mu} + 1{,}75$$

f_S = sphericity, the ratio of surface area of the ball to the real surface area of the particle in the same volume

e = bed porosity, the ratio between space with the volume of the bed

V_o = superficial velocity, V_o = V.e, V = average velocity

L = height of the bed

r = density of fluid

D_p = particle (packing) diameter

Bed porosity: 0,55 – 0,75

ΔP = P1 - P2

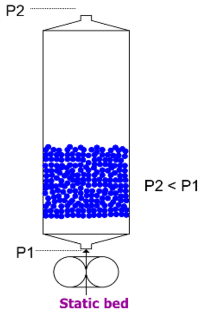


Figure 2.6 Schematic of static bed

When a fluid flowrate was increased then the pressure drop of the solid particle will follow.

When the flowrate increased continually, the solid particle will be fluidised, and the pressure drop remain constant.

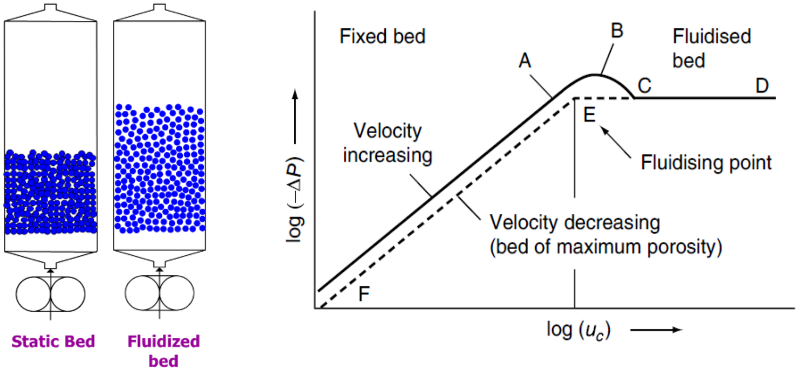


Figure 2.7 Schematic of static and fluidized bed with diagram of pressure drop over fixed and fluidized bed

When the flowrate continuedly increased the solid particle will move along with the fluid and act as fluid, thus can be used for solid transportation especially fine particles (pneumatic conveyor).

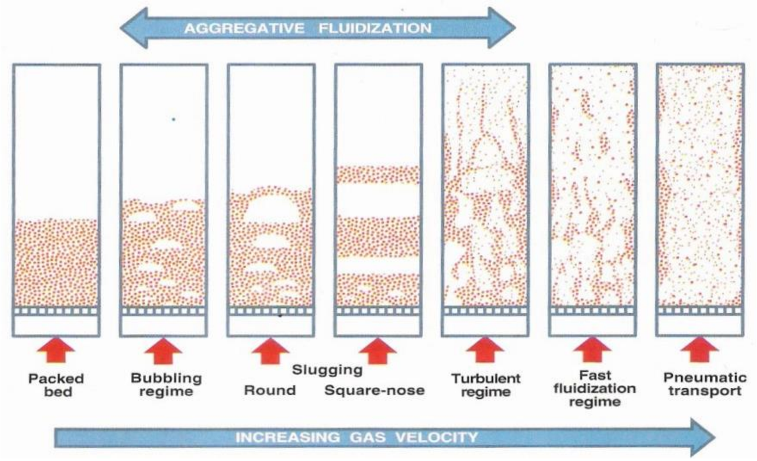


Figure 2.8 Various regime profile of fluidization

Pressure drops and height of bed

Consider a vertical tube partly filled with a fine granular material such as catalytic cracking catalyst. The tube is open at the top and has a porous plate at the bottom to support the bed of catalyst and to distribute the flow uniformly over the entire cross section. Air is admitted below the distributor plate at a low flow rate and passes upward through the bed without causing any particle motion. If the particles are quite small, flow in the channels between the particles will be laminar and the pressure drop across the bed will be proportional to the superficial velocity, $\tilde{V}_0$.

As the velocity is gradually increased, the pressure drop increases, but the particles do not move and the bed height remains the same. At a certain velocity, the pressure drop across the bed counterbalances the force of gravity on the particles or the weight of the bed, and any further increase in velocity causes the particles to move. This is point *A on the graph. Sometimes the bed expands* slightly with the grains still in contact, since just a slight increase in ε *can offset* an increase of several percent in $\tilde{V}_0$ *and keep* Δp *constant. With a further increase* in velocity, the particles become separated enough to move about in the bed, and true fluidization begins (point *B).*

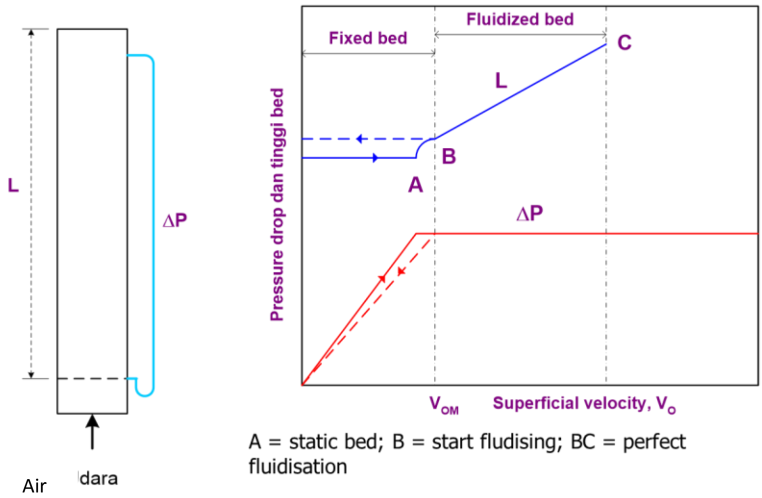
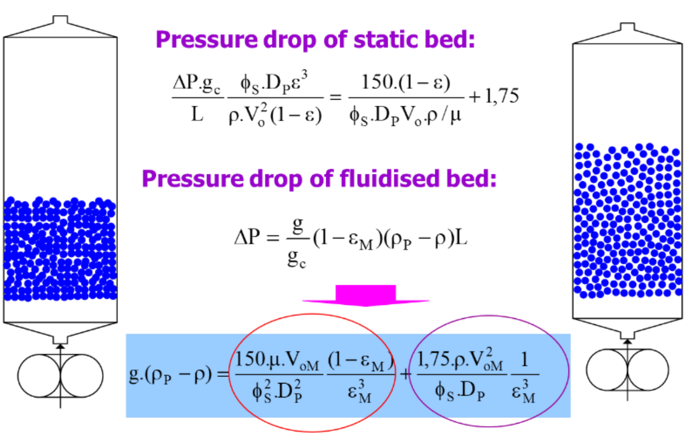


Figure 2.9 Correlations of pressure drops and height of bed

Once the bed is fluidized, the pressure drop across the bed stays constant, but the bed height continues to increase with increasing flow. The bed can be operated at quite high velocities with very little or no loss of solids, since the superficial velocity needed to support a bed of particles is much less than the terminal velocity for individual particles, as will be shown later. If the flow rate to the fluidized bed is gradually reduced, the pressure drop remains constant, and the bed height decreases, following the line *BC which* *was* observed for increasing velocities. The final bed height may be greater than the initial value for the fixed bed, since solids dumped in a tube tend to pack more tightly than solids slowly settling from a fluidized state. The pressure drop at low velocities is then less than in the original fixed bed. On starting up again, the pressure drop offsets the weight of the bed at point B, and this point, rather than point A, should be considered to give the minimum fluidization velocity, $\tilde{V}_{0M}$.

To measure $\tilde{V}_{0M}$, the bed should be fluidized vigorously, allowed to settle with the gas turned off, and the flow rate increased gradually until the bed starts to expand. More reproducible values of $\tilde{V}_{0M}$ *can sometimes be obtained* from the intersection of the graphs of pressure drop in the fixed bed and the fluidized bed.

Minimum fluidising velocity



Two extreme conditions:

$$g.(\rho_P - \rho) = \frac{150.\mu.V_{oM}}{\phi_S^2.D_P^2}\frac{(1-\varepsilon_M)}{\varepsilon_M^3} + \frac{1{,}75.\rho.V_{oM}^2}{\phi_S.D_P}\frac{1}{\varepsilon_M^3}$$

$N_{Re,P} < 1$

$$g.(\rho_P - \rho) = \frac{150.\mu.V_{oM}}{\phi_S^2.D_P^2}\frac{(1-\varepsilon_M)}{\varepsilon_M^3}$$

$$V_{oM} = \frac{g.(\rho_P - \rho)}{150.\mu}\frac{\varepsilon_M^3}{(1-\varepsilon_M)}\phi_S^2.D_P^2$$

$N_{Re,P} > 1000$

$$g.(\rho_P - \rho) = \frac{1{,}75.\rho.V_{oM}^2}{\phi_S.D_P}\frac{1}{\varepsilon_M^3}$$

$$V_{oM} = \sqrt{\frac{\phi_S.D_P.g.(\rho_P - \rho)\varepsilon_M^3}{1{,}75.\rho}}$$

Particle's Reynold number:

$$N_{Re,P} = \frac{D_P.U_t.\rho}{\mu}$$

D_P = particle diameter
U_t = terminal velocity
ρ = fluid density
μ = fluid viscosity

$N_{Re,P} < 1000$

$$U_t = \frac{g.D_P^2(\rho_P - \rho)}{18.\mu}$$

$N_{Re,P} = 1000 - 20000$

$$U_t = \sqrt{\frac{1{,}75.g.D_P(\rho_P - \rho)}{\rho}}$$

Laminar flow, $N_{Re,P} < 1$ and small size particles:

$$\frac{U_t}{V_{o,M}} = \frac{g.D_P^2(\rho_P - \rho)}{18.\mu}\frac{150.\mu}{g.(\rho_P - \rho).\phi_S^2.D_P^2}\frac{(1-\varepsilon_M)}{\varepsilon_M^3} = \frac{8{,}33.(1-\varepsilon_M)}{\phi_S^2.\varepsilon_M^3}$$

$N_{Re,P} > 1000$ dan $D_P > 1$ mm

$$\frac{U_t}{V_{o,M}} = 1{,}75\left[\frac{g.D_P^2(\rho_P - \rho)}{\rho}\right]^{1/2}\left[\frac{1{,}75.\rho}{g.D_P^2.(\rho_P - \rho).\varepsilon_M^3}\right]^{1/2} = \frac{2{,}32}{\varepsilon_M^{3/2}}$$

Geldart's Classic Classification of Powders

Group A is designated as 'aeratable' particles. These materials have small mean particle size (dp < 30 μm) and/or low particle density (<~1.4 g/cm3). Fluid cracking catalysts typically are in this category. These solids fluidize easily, with smooth fluidization at low gas velocities without the formation of bubbles.

Group B is called 'sandlike' particles and some call it bubbly particles. Most particles of this group have size 150 μm to 500 μm and density from 1.4 to 4 g/cm3. For these particles, once the minimum fluidization velocity is exceeded, the excess gas appears in the form of bubbles. Bubbles in a bed of group B particles can grow to a large size. Typically used group B materials are glass beads (ballotini) and coarse sand.

Group C materials are 'cohesive', or very fine powders. Their sizes are usually less than 30 μm, and they are extremely difficult to fluidize because interparticle forces are relatively large, compared to those resulting from the action of gas. In small diameter beds, group C particles easily give rise to channelling. Examples of group C materials are talc, flour and starch.

Group D is called 'spottable' and the materials are either very large or very dense. They are difficult to fluidize in deep beds. Unlike group B particles, as velocity increases, a jet can be formed in the bed and material may then be blown out with the jet in a spouting motion. If the gas distribution is uneven, spouting behaviour and severe channelling can be expected. Roasting coffee beans, lead shot and some roasting metal ores are examples of group D materials.

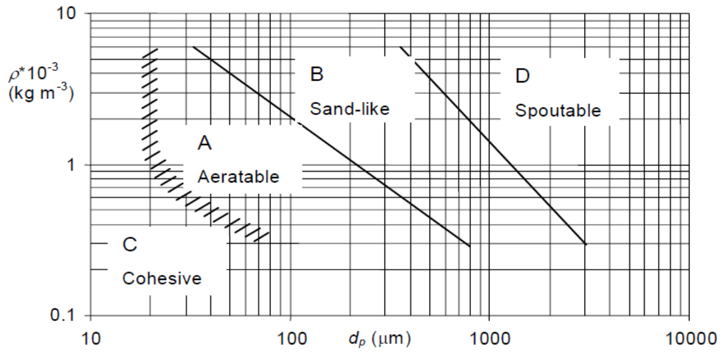


Figure 2.10 Diagram of Geldart classification of particles

When talking about a fluidized bed, mostly one refers to a bubbling fluidized bed type as shown in Fig. 2.1C. Gas fluidized beds are characterized by the 'bubbles' which form at superficial gas velocities only slightly higher than that required to just fluidize the particles.

This type of fluidization has been called 'aggregative fluidization', and under these conditions, the bed appears to be divided into two phases, the bubble phase and the emulsion phase. The bubbles appear to be very similar to gas bubbles formed in a liquid and they behave in a similar manner. The bubbles coalesce as they rise through the bed.

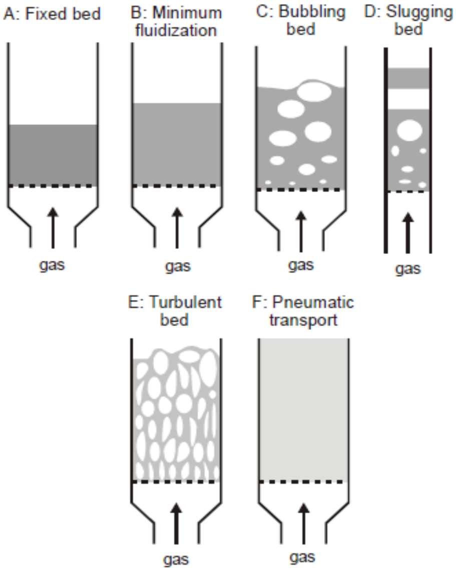


Figure 2.11 Schematic representation of fluidized beds in different regimes

2.1.b Type of Fluidization

1. Particulate Fluidization

$$\left(N_{Fr}.N_{Re}\right)\frac{(\rho_p - \rho)}{\rho}\frac{L}{D} < 100$$

Prediction $\varepsilon^3/(1-\varepsilon)$ proportional with V_0 at higher value from V_{0M}

$$\frac{\varepsilon^3}{1-\varepsilon} = \frac{150.V_o.\mu}{g.(\rho_P - \rho).\phi_S^2.D_P^2}$$

$$L = L_M\frac{1-\varepsilon_M}{1-\varepsilon}$$

L = height of the bed

L_M = minimum height of the bed

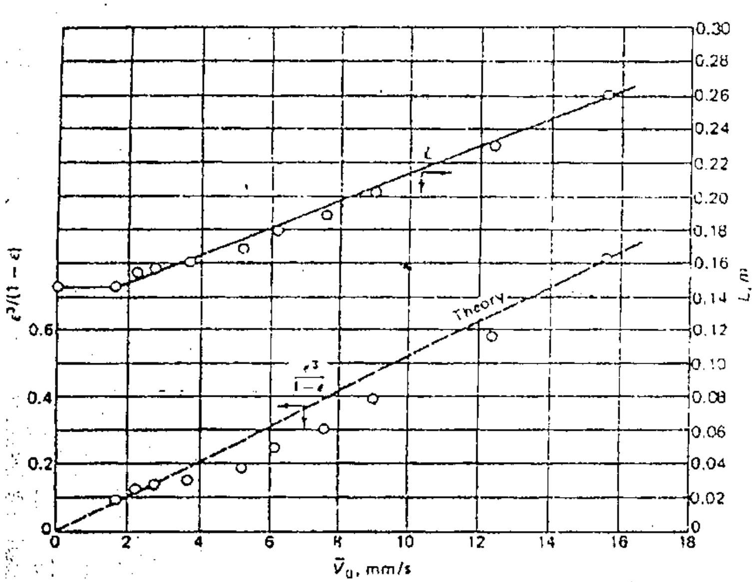


Figure 2.12 Profile of bed expansion in particulate fluidization ($\varepsilon^3/(1 - \varepsilon)$ is proportional to V_0 for values greater than $\tilde{V}_{OM}$)

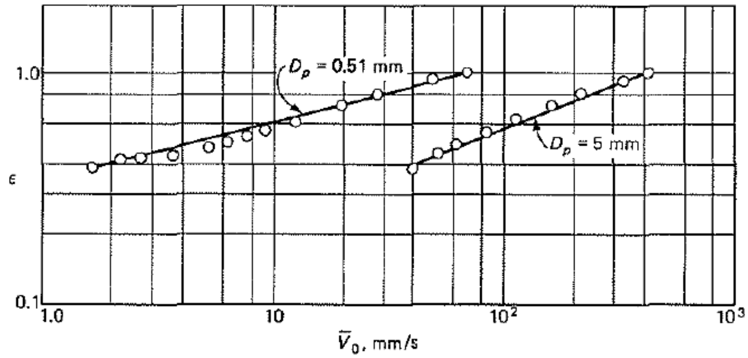


Figure 2.13 Variation of porosity with fluid velocity in fluidized bed, Data for the fluidization of small glass beads (510 μm) in water

2. Aggregative / Bubbling Fluidization

$$(N_{Fr}.N_{Re})\frac{(\rho_p - \rho)}{\rho}\frac{L}{D} > 100$$

$$\frac{\Delta P}{L} = \frac{g}{g_c}.(1-\varepsilon).(\rho_P - \rho)$$

Pressure drop constant per unit height of the bed

The expansion is granular with the flow of the bubbles. Correlation between fraction of the space filled with the granular phase and velocity:

$$V_o = t_b u_b + (1 - t_b) V_{o,M}$$

tb = fraction of the space filled with the bubbles

ub = average bubble velocity

$$\frac{L}{L_M} = \frac{u_b - V_{o,M}}{u_b - V_o} \qquad u_b = \sqrt{0,7.g.D_p}$$

2.2 Exercise

A bed of ion-exchange beads 8 ft deep is to be back washed with water to remove dirt. The particles have a density 1.24 g/cm^3 and an average size of 1.1 mm. What is the minimum fluidization velocity using water at 20°C, and what velocity is required to expand the bed by 25 percent? The beads are assumed to be spherical (Φ = 1) and ε_M is taken as 0.40.

3. End of Chapter 2

3.1 Summary

Fluidization is a process whereby a granular material is converted from a static solid-like state to a dynamic fluid-like state. Fluidization application can be found in the chemical engineering unit operation that applied fluidization concept such as reactor (fluidized bed reactor), dryer (fluidized bed dryer) and particle transportation.

Fluidization can be modelled by Ergun equation:

$$\frac{\Delta P.g_c}{L}\frac{\phi_S.D_P\varepsilon^3}{\rho.V_o^2(1-\varepsilon)} = \frac{150.(1-\varepsilon)}{\phi_S.D_P V_o.\rho/\mu} + 1{,}75$$

f_S = sphericity, the ratio of surface area of the ball to the real surface area of the particle in the same volume

e = bed porosity, the ratio between space with the volume of the bed

V_o = superficial velocity, V_o = V.e, V = average velocity

L = height of the bed

r = density of fluid

D_p = particle (packing) diameter

Bed porosity: 0,55 – 0,75

ΔP = P1 - P2

3.2 Exam

Fluidised reactor use solid catalyst with 0.1 mm in diameter, density of the particle 1.50 g/mL, sphericity 0.92. In the static bed the porosity is 0.35, with the height of the bed 2 m. Gas was introduced from the bottom of the reactor with temperature 600^0C, 1 atm pressure, viscocity 0.025cP, and density 0.22 lb/cuft. In minimum fluidising velocity the porosity was up to 0.45. What will be the superficial velocity of the gas entered the bed if the catalyst fluidisation porosity 0.52

3.3 Feedback

Successful completion of this chapter is measured by the ability of students to explain the concept of fluidization and the phenomenon of fluidization, the parameters in fluidization and the use of fluidization in the industry as well as analyse, evaluate and design (C6) the fluidization system.

3.4 Following action

Students can practice solving the fluidization problem which are available in reference book. After that, students can continue to read the following chapters.

3.5 Solution

		cgs	british
Particle diameter, D_P	0,1 mm	0,01	3,28 x 10^{-4}
Density of the particle, ρ_P	1,50 g/ml	1,5	93,645

		cgs	british
Spericity, ϕ	0,92	0,92	0,92
Porosity of the static bed, ε_D	0,35	0,35	0,35
Height of the static bed, L_M	2 m	200	6,56
Temperature gas, T	600 °C		
Pressure gas, P	1 atm		
Viscosity gas, μ	0,025 cP	0,00025	$1{,}68 \times 10^{-5}$
Density of gas, ρ_g	0,22 lb/cuft	0,003524	0,22
Porosity of minimum fluidisation, ε_M	0,45	0,45	0,45
Porosity of the fluidised catalyst, ε	0,52	0,52	0,52
Gravitation, g		980,665	32,174

$$V_o = \frac{g.(\rho_P - \rho)}{150.\mu} \frac{\varepsilon^3}{(1-\varepsilon\ )} \phi_S^2 . D_P^2$$

$$V_o = \frac{980{,}665x(1{,}50 - 0{,}003524)}{150x0{,}00025} \frac{0{,}52^3}{(1-0{,}52)} x0{,}92^2 x0{,}01^2$$

$$V_o = 0{,}97\ cm/s$$

$$V_o = 0{,}032\ ft/s$$

References

1. D. Kunii Octave Levenspiel., 2013. U Fluidization Engineering 2nd Edition, Butterworth-Heinemann.
2. Brown, G.G., Kate, D., Foust, A.S., and Schneidewind, R. 1950. Unit Operations. New York: Jhon Wiley & Sons, Inc.
3. Darby, R. 1932. Chemical Engineering Fluid Mechanics. New York: Marcel Dekker.

Glossary

Sphericity is the ratio of surface area of the ball to the real surface area of the particle in the same volume

CHAPTER 3
FILTRATION

1. Introduction

1.1 Brief Description

This chapter discussed about definition of filtration, type of industrial filtration, process parameters of filtration and selection of filters.

1.2 Relevance

Filtration is a common process used in the industry and has a wide range of application. The ability to understand the basic principle, type and application of filtration system for specific purposes is necessary for the students.

1.3 Learning Outcome

After completing the course students will be able to design (C6) chemical engineering operations units including a complex integrated system consisting of several operating units. In details, students will be able to:

a) explain (C2) the basic concepts of the filtration process

b) apply (C3) specific type of filtration for particular system

1.4 Learning Instruction

Read the Chapter 3 along with other complementary supplements such as, Unit Operations of Chemical Engineering, by Mc Cabe et al 1993 and Unit Operation by Brown, 1950. Source from the internet also can be added to see the development of filtration system. Work on the exercise and quizzes for improve the learning outcome achievements.

2. Materials

2.1 Materials Description

Definition

Filtration may be defined as the separation of solid from a fluid by means of a porous medium that retains the solid but allows the fluid to pass. The suspension of solid and liquid to be filtered is known as the slurry. The porous medium used to retain the solids is described as the filter medium; The accumulation of solids on the filter is referred to as the filter cake, while the clear liquid passing through the filter is the filtrate.

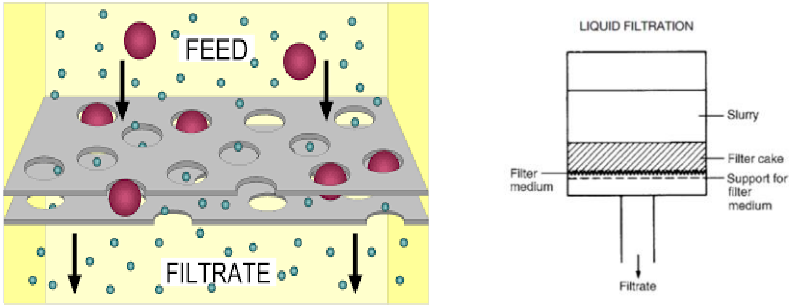


Figure 3.1 The schematic diagram of filtration concept

Driving force of the filtration process:

- Gravity
- Pressure (Vacuum)
- Centrifugal force

In general, pores of the medium > the particles size which are to be removed. Filter works efficiently after an initial deposit (cake) has been trapped in the medium

In the laboratory: Filtration is carried out using Buchner funnel and the liquid is sucked through thin layer of particles using vacuum or conical funnel fitted with filter paper.

In the industrial application: Difficulties are encountered in the mechanical handling such as applying high pressure and greater area needed.

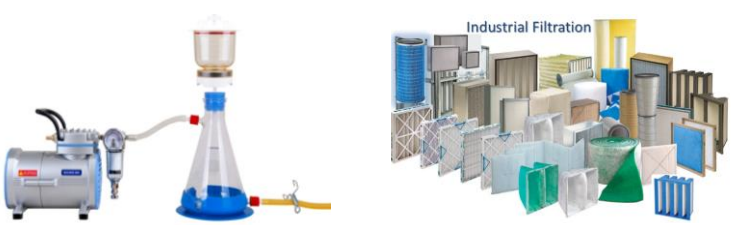


Figure 3.2 Laboratory vs industrial filtration system

Type of industrial filtration

- Gravity filters
- Pressure filters
- Vacuum filters
- Centrifugal filters

Gravity filters

The oldest and simplest type consist of tanks (wood, steel. Metal, concrete) with perforated bottoms filled with porous media, fluid passes in laminar flow, widely used to the process large quantities of fluid containing small quantities of solids and water purifications.

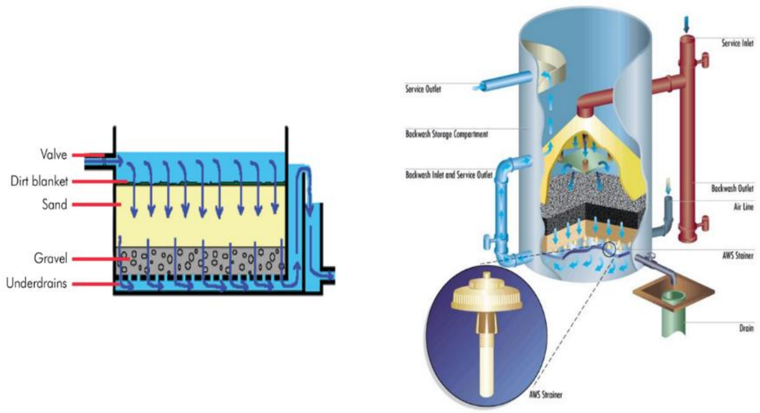


Figure 3.3 Schematic visualization of horizontal and vertical gravity filters

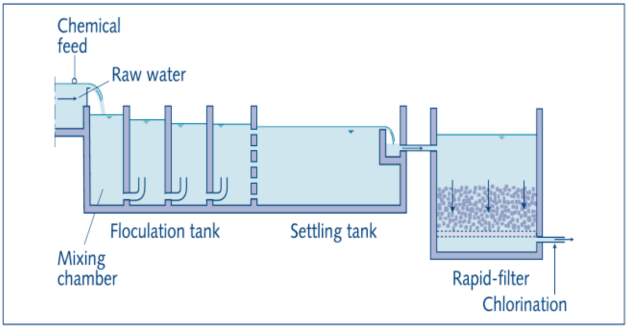


Figure 3.4 Schematic diagram of horizontal gravity filters integrated with other process

Figure 3.5 Industrial scale of horizontal gravity filter

Pressure filters

Due to the formation of cakes occurs in low permeability, many types of slurry require higher pressure difference for effective filtration than can be achieved by applying pressure or vacuum techniques.

There are four main basic types of filter presses:

1. plate and frame filter press
2. recessed plate and frame filter press

Plate and frame filter press This press is made up of two units, known respectively as plates and frames, with a filter medium, usually filter cloth, between the two. The frame is open, with an inlet for the slurry, while the plate has grooved surface to support the filter cloth, and with an outlet for the filtrate.

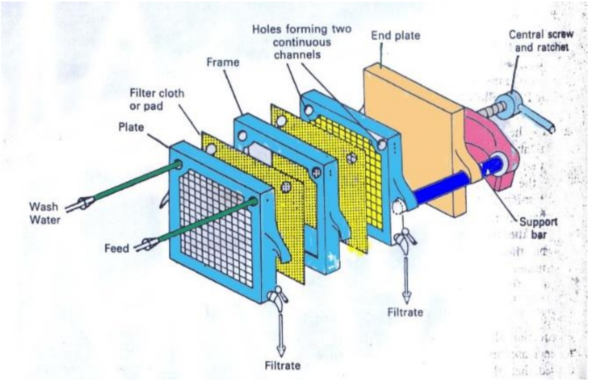
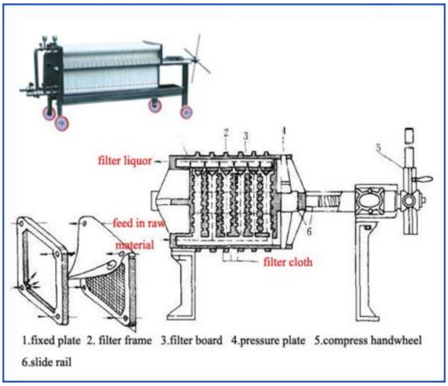


Figure 3.6 Schematic visualization of filter press

Plates and frames may be made in various metals to provide resistance to corrosion or prevent metallic contamination of the product. Non-metals e.g. plastics is lighter, also varieties of wood are satisfactory materials of construction. Plates and frames may be of considerable size, of about 1m square.



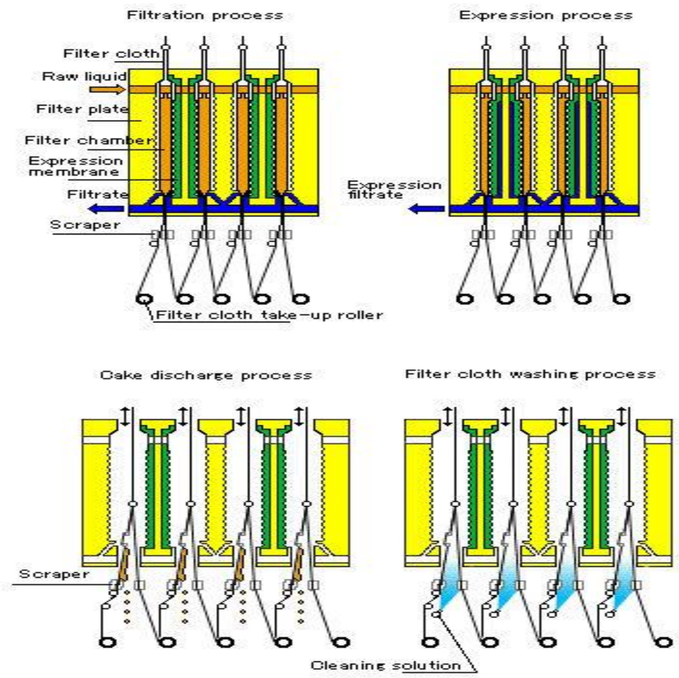


Figure 3.7 Steps of filtration process in the filter press

Advantages:

- Construction is very simple, and a wide variety of materials can be used.
- It provides a large filtering area in a relatively small floor space.
- It is versatile, the capacity being variable according to the thickness of the frames and the number used.
- The construction permits the use of considerable pressure difference.
- Efficient washing of the cake is possible.
- Operation and maintenance are straightforward

Disadvantages:

- Time consuming due to batch
- Expensive as the process time, the labour, and the wear and tear on the cloths demands high costs.
- Operation is critical, as the frames should be full, otherwise washing is inefficient and the cake is difficult to remove.
- The filter press is used for slurries containing less about 5% solids
- Suitable for expensive materials e.g.: the removal of precipitated proteins from insulin liquors.

Vacuum filters

- Vacuum filters operate practically at higher pressure differentials than gravity filters
- Rotary vacuum filter and the leaf filter are most extensively used

Leaf filters. Similar to plate and frame filters in that a cake is deposited on each side of the leaf and the filtrate flows to the outlet channel provided by the coarse drainage screen in the leaf between the cakes. Consisting of a frame enclosing a drainage screen or grooved plate, the whole unites being covered with filter cloth. The outlet for the filtrate connects to the inside of the frame, which represents a vertical section through the leaf. The frame may be circular, square, or rectangular shapes.

The operation: The leaf filter is immersed in the slurry and a receiver, and a vacuum system connected to the filtrate outlet.

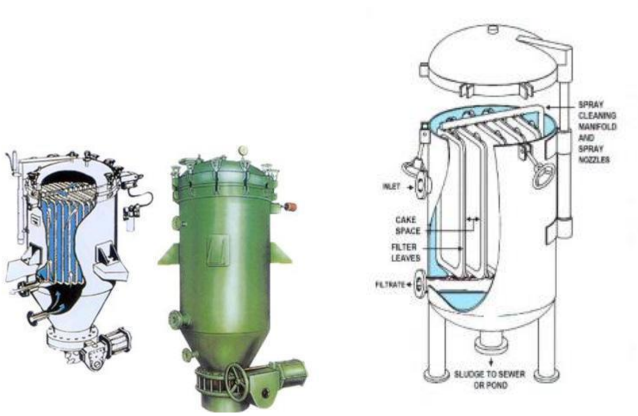


Figure 3.8 Leaf filter and the schematic diagram of stacking leaf inside the chamber

Advantages:

- The slurry can be filtered from any vessel.
- The cake can be washed simply by immersing the filter in a vessel of Water.
- Removal of the cake is facilitated by the use of reverse air flow.
- The filter can be modified by employing a suitable number of unites.
- The leaf filter is most satisfactory if the solids content of the slurry is not too high, 5 % being a suitable maximum.
- Labour costs for operating the filter are comparatively moderate.

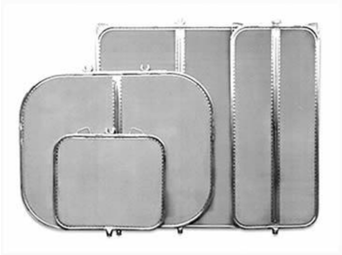


Figure 3.9 Various industrial size pf leaf filter medium

Rotary vacuum filter:

- Most widely used
- Large scale applications
- Filter slurries containing a high proportion of solids.
- Continuous process and has a system for removing the cake
- Suitable for use with concentrated slurries.
- It is a metal cylinder mounted horizontally, the curved surface being a perforated plate, supporting a filter cloth. Internally, it is divided into several sectors and a separate connection is made between each sector and a special rotary valve.

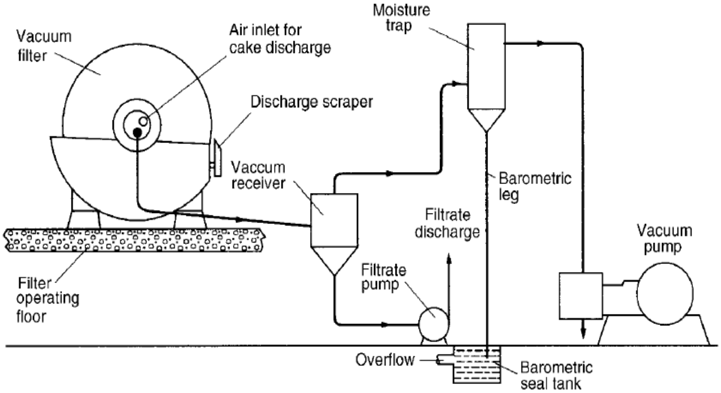


Figure 3.10 Schematic diagram of rotary vacuum filter system

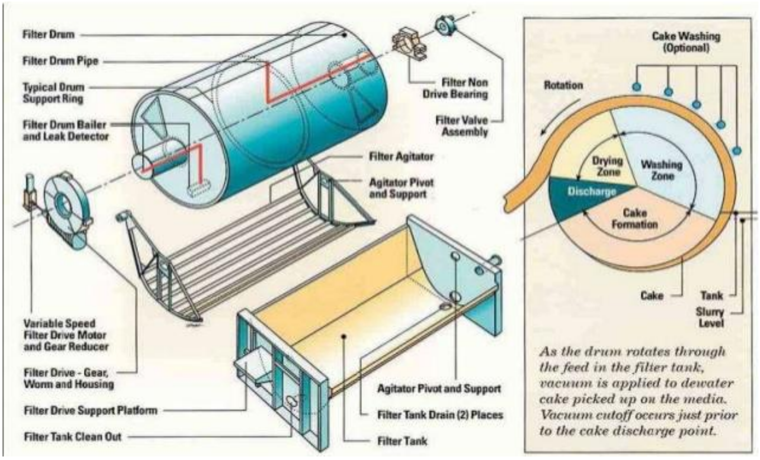


Figure 3.11 Filter drum partition and the filtration zone created during the process

Operation:

- The drum is immersed to the required depth in the slurry, which is agitated to prevent settling of the solids, and vacuum is applied to those sectors of the drum which is submerged.
- A cake of the desired thickness is produced by adjusting the speed of rotation of the drum. Each sector is immersed in turn in the slurry and the cake is then washed and partially dried by means of a current of air.
- Finally, pressure is applied under the cloth to aid the removal of the cake.
- Removal of the washed and partially dried cake is affected by means of a doctor knife.

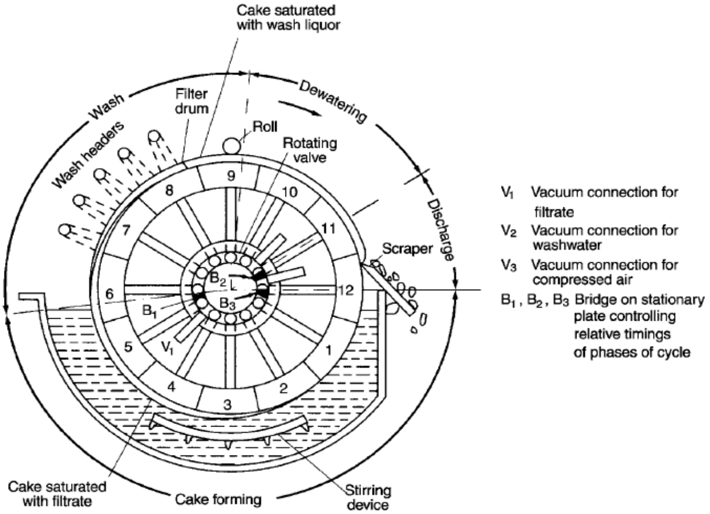


Figure 3.12 Cross section visualization of the filtration zone during the process

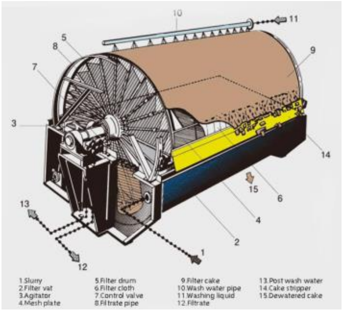


Figure 3.13 Industrial scale of rotary vacuum filter

Uses:

- The rotary filter for continuous operation on large quantities of slurry.
- Suitable for slurry contains considerable amounts of solids in the range 15-30%.

- Examples of pharmaceutical application include the collection of calcium carbonate, magnesium carbonate, and starch, and the separation of the mycelium from the fermentation liquor in the manufacture of antibiotics

Advantages:

- The rotary filter is automatic and is continuous in operation, so that the labour costs are very low.
- The filter has a large capacity, so it is suitable for the filtration of highly concentrated solutions.
- Variation of the speed of rotation enables the cake thickness to be controlled.
- Pre-coat of filter aid could use to accelerate the filtration rate.

Disadvantages:

- The rotary filter is a complex of equipment, with many moving parts and is very expensive.
- In addition to the filter itself, some accessories are connected, e.g. a vacuum pump, vacuum receivers, slurry pumps and agitators are required.
- The cake tends to crack due to the air drawn through by the vacuum system, so that washing and drying are not efficient.
- Being a vacuum filter, the pressure difference is limited to 1 bar and hot filtrates may boil.

Centrifugal filters

A centrifuge consists of a basket in which mixture of solid and liquid, or mixture of two liquids is rotated at high speed so that it is separated into its constituents by the action of centrifugal force.

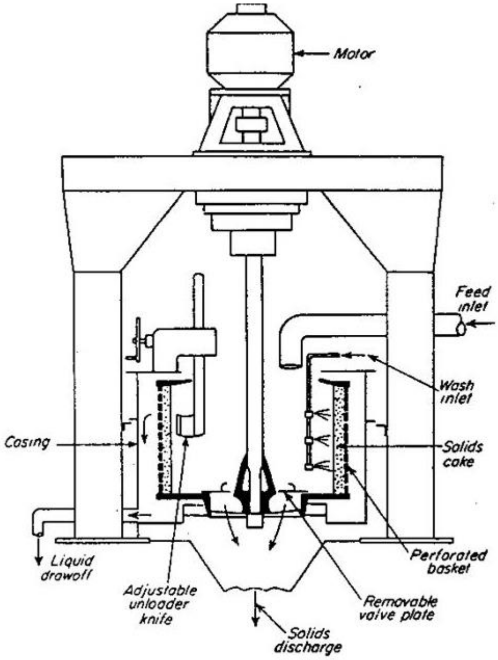


Figure 30-19 Top-suspended basket centrifugal.

Figure 3.14 Centrifugal filter

Perforated basket centrifuge. A vessel about 1 m in diameter and its outer wall is perforated. It is mounted on a vertical shaft by means it can be rotated at a high speed. An outer casing with an outlet collects the liquid thrown out from the basket. The drive motor may be below the centrifuge, and it is called under-driven.

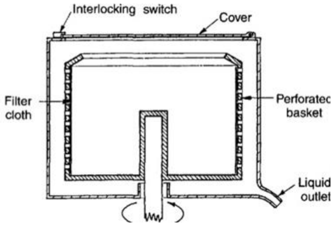


Figure 3.15 Perforated basket centrifuge filter

The pusher-type centrifuge. Pusher centrifuges, also called horizontal basket centrifuges, possess filtration bowls equipped with metal screening sheets or slotted sieves. These systems also filter liquids in the centrifugal field and retain solids as filter cakes in the bowls. An oscillating pushing motion transports the cakes out of the bowls. Solids may also be washed with these systems.

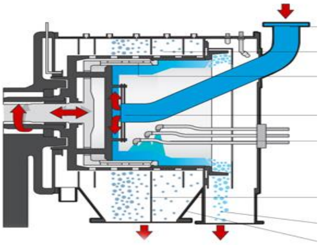


Figure 3.16 The pusher-type centrifuge filter

Tubular centrifuge. High centrifugal effects can be obtained by using a centrifuge of small diameter rotated at a high speed.

Uses:

- It can separate solids of small particle size from liquids.

- It can be used to separate immiscible liquids from one another e.g. the two components of emulsion.
- It can be used for filtration of very diluted suspensions i.e. solutions containing very low concentration of solids.

Figure 3.17 Tubular centrifuge filter

Process parameters of filtration

Filtration is affected by the characteristics of the slurry, including:

- The properties of the liquid, such as density, viscosity, and corrosiveness.
- The properties of the solid, for example, particle shape, particle size, particle size distribution, and the rigidity or compressibility of the solid.
- The proportion of solids in the slurry.
- Whether the objective is to collect the solid, the liquid, or both.

- Whether the solids have to be washed free from the liquid or a solute.

Rate Of Filtration

The factors affecting rate of filtration is known as Darcy's law and may be expressed as:

$$\frac{dV}{dt} = \frac{KAP}{\mu l}$$

Where:

V = volume of filtrate

t = time of filtration

K = constant for the filter medium and filter cake

A = area of filter medium

P = pressure drop across the filter medium and filter cake

μ = viscosity of the filtrate

l = thickness of cake

The rate of filtration depends on:

- The drop in pressure from the feed to the far side of the filter medium
- The area of the filtering surface
- The viscosity of the filtrate
- The resistance of the filter cake
- The resistance of the filter medium and initial layer of cake

The other parameters:

Permeability coefficient: The constant (K) represents the resistance of both the filter medium and the filter cake. As the thickness of the cake increase, the rate of filtration will decrease. Also, the surface area of the particles, the porosity of the cake, and rigidity or compressibility of the particles could affect the permeability of the cake.

Area of filter medium: The total volume of filtrate flowing from the filter will be proportional to the area of the filter. The area can be increased by using larger filters. In the rotary drum filter, the continuous removal of the filter cake will give an infinite area for filtration.

Pressure drop: The rate of filtration is proportional to the pressure difference across both the filter medium and filter cake.

The pressure drop can be achieved in several ways:

- Gravity: A pressure difference could be obtained by maintaining a head of slurry above the filter medium. The pressure developed will depend on the density of the slurry.
- Vacuum: The pressure below the filter medium may be reduced below atmospheric pressure by connecting the filtrate receiver to a vacuum pump and creating a pressure difference across the filter.
- Pressure: The simplest method being to pump the slurry into the filter under pressure.
- Centrifugal force: The gravitational force could be replaced by centrifugal force in particle separation

Viscosity of filtrate: It would be expected that an increase in the viscosity of the filtrate will increase the resistance of flow, so that the rate of filtration is inversely proportional to the viscosity of the fluid.

This problem can be overcome by two methods:

- The rate of filtration may be increased by raising the temperature of the liquid, which lowers its viscosity. However, it is not practicable if thermolabile materials are involved or if the filtrate is volatile.
- Dilution is another alternative, but the rate must be doubled

Thickness of filter cake: The rate of flow of the filtrate through the filter cake is inversely proportional to thickness of the cake. Preliminary decantation may be useful to decrease the amount of the solids.

Selection of filters

Ideally the equipment chosen should allow a fast filtration rate to minimize production costs, be cheap to buy and run, be easily cleaned and resistant to corrosion, and be capable of filtering large volumes of products. There are a number of products – related factors that should be considered when selecting a filter for a particulate process.

1. The chemical nature of the product. Interactions with the filter medium may lead to leaching of the filter components, degradation or swelling of the filter medium or adsorption of components of the filtered product on the filter. All of these

may influence the efficiency of the filtration process or the quality of the filtered product.

2. The volume to be filtered and the filtration rate required.
3. The operating pressure needed. This is governing the filtration rate
4. The amount of material to be removed. Prefilters (decantation) may be required or filter where the cake can be continuously removed.
5. The degree of filtration required. This affect the chosen pore size of membrane filters or the filter grade to be used.
6. If sterility is required, then the equipment should itself be capable of being sterilized and must ensure that contamination does not occur after the product has passed the filter.
7. The product viscosity and filtration temperature. A high product viscosity may require elevated pressure to be used.

Table 3.1 Additional filtration system selection rule of thumbs

	Filter Press	**Continuous Vacuum and Pressure**	**Nutsche Filter and Filter Dryer**	**Clarification**
Solid content the suspension (%)	5-30	10-40	10-40	<5
Maximum pressure difference	100 bar	-1 to 6 bar	6 bar	10 bar
Cake thickness (mm)	5-50	5-150	5-300	20
Average particle size	1-100 microns	1-100 microns	5-200 microns	1-50 microns
Type of operation	Batch	Continuous	Batch	Batch
Comments	Good for slow filtration and can produce dry filter cake	Excellent cake washing and predrying	Good when reactor batch times equal to total cycle times	Disposable for low flows; candle and plate filters for large flow

2.2 Exercise

A unit of filtration system is needed for collection of calcium carbonate. The slurry contains 33% of calcium carbonate that needs to be separated. The system is required to have capacity 75 kg/ft.h. Suggest one type of filtration system for the said process.

3. End of Chapter 3

3.1 Summary

Selecting a filtration technology requires a systems approach that must be incorporated with other solids processing such as reactors, dryers, solids handling, and others. The engineer "is not normally involved in the detailed design of the equipment; just selects and specifies the equipment needed for a particular process and consults with the vendors to ensure that the equipment is suitable". The process has three components that must be considered: material properties, mechanical properties, and separation performance. These are combined and the ranked choices must then be evaluated weighing operational, economic, and plant (internal and external) objectives. The more information the engineer can provide about the process and the requirements, the better the accuracy of the vendor's information.

3.2 Exam

A unit of filtration system is needed for fruit juice clarification. The fruit juice contains 12% of pulps that needs to be separated from the fruit juice. The system is required to have capacity 250 L/m.h. Suggest one type filtration system for the said process and explain in detail the reason for the suggestion including its basic principle and mechanism.

3.3 Feedback

Successful completion of this chapter is measured by the ability of students to explain the basic concepts of the filtration process and apply a specific type of filtration for particular system.

3.4 Following action

Students may form groups and make a summary on many other types of filtration system such as Rotary drum: Disk type filter, Rotary drum: Top feeder filter, Rotary drum: Precoat filter, Perforated centrifuge filter, Pushed type centrifuge filter, Tubular centrifuge filter, Disk Bowl centrifuge filter. After that, students can continue to read the following chapters.

3.5 Solution

Some options for fruit juice clarification with pulps 12% and capacity 1250 L/m.h are rotary vacuum filter or centrifugal filter as the solid ratio and the capacity fit the specification as well as the possibility to be operated in the continuous mode.

References

1 Warren L. McCabe, Julian C. Smith, Peter Harriott., 1993. Unit Operations of Chemical Engineering, 5th Edition, Singapore: McGraw-Hill.

2 Brown, G.G., Kate, D., Foust, A.S., and Schneidewind, R. 1950. Unit Operations. New York: Jhon Wiley & Sons, Inc.

3 Green, D.W. and Maloney, J.O. 1997. Perry's Chemical Engineers Handbook. USA: Mc Graw Hill Ltd.

Glossary

Darcy's Law is an equation that describes the flow of a fluid through a porous medium

CHAPTER 4
FLOTATION

1. Introduction

1.1 Brief Description

This chapter discussed about definition, flotation mechanism, chemical additives to enhance flotation processes, characterization of flotation separations, flotation equipment: conventional flotation techniques, devices and processes, emerging flotation techniques and processes, and application.

1.2 Relevance

Flotation is a process used in specific industry such as mining ores and some other separation system. The compactness in comparison with other technology can be develop further for many other applications. The ability to understand the flotation mechanism, chemical additives to enhance flotation processes, characterization of flotation separations, flotation equipment and application for specific purposes is necessary for the students.

1.3 Learning Outcome

After completing the course students will be able to design (C6) chemical engineering operations units including a complex integrated system consisting of several operating units. In details, students will be able to:

a) explain (C2) the principles of flotation

b) application (C3), and flotation process system

1.4 Learning Instruction

Read the Chapter 4 along with other complementary supplements such as, Unit Operations of Chemical Engineering, by Mc Cabe et al 1993 and Unit Operation by Brown, 1950. Source from the internet also can be added to see the development of flotation system. Work on the exercise and quizzes for improve the learning outcome achievements.

2. Materials

2.1 Materials Description

Flotation is a separation process based on the use of very fine gas bubbles that attach themselves to the solid particles in suspension to make them buoyant and drive them toward the free surface of the liquid.

Figure 4.1 Flotation system in the industry

Many advantages have been reported illustrating the technical and economic potential of this process:

- high selectivity to recover valuables (Au, Pt, Pd, etc);
- high efficiency to remove contaminants: high overflow rates, low detention periods (meaning smaller tank sizes, less space needs, savings in construction costs);
- low operating costs with the use of upcoming flotation devices
- can provide high float concentration (good thickening)
- can remove low density particles which would require long settling periods.

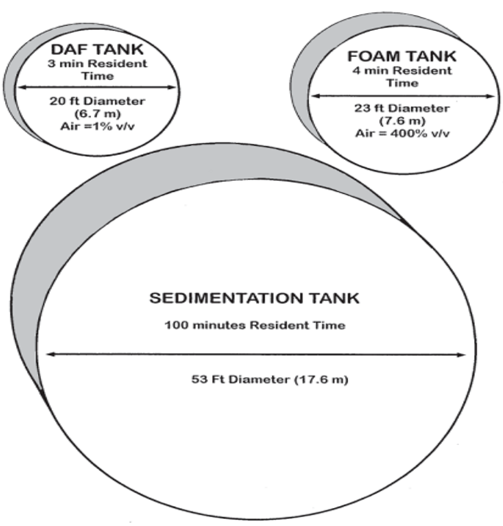


Figure 4.2 Flotation system in the industry

Flotation Mechanism

1. Air bubbles generation

Bubbles are formed by a reduction in pressure of water (treated feed recycled) pre-saturated with air at pressures higher than atmospheric (3 to 6 atm)

2. Attachment of a specific mineral particle to air bubbles
3. Being carried by the water in liquid surface

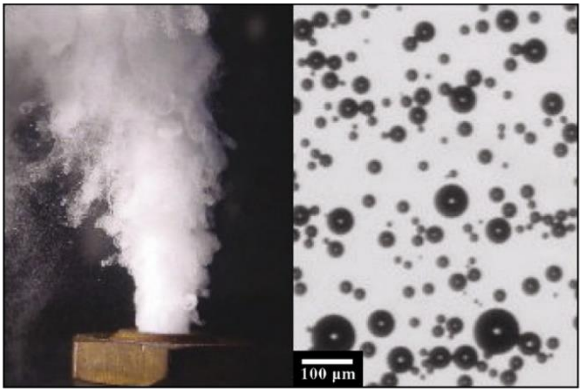


Figure 4.3 The generation of the microbubbles, exploring the air dissolution under pressure

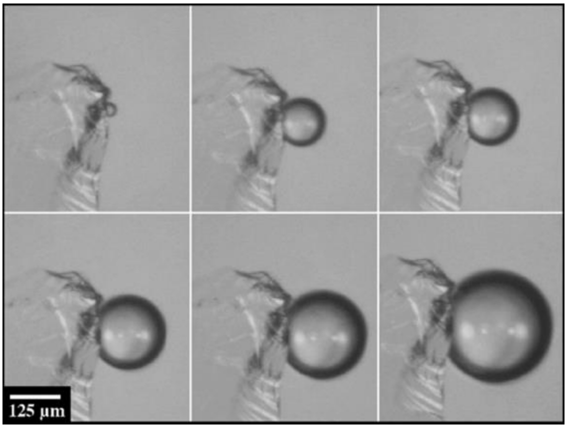


Figure 4.4 Mechanisms involved in the interaction between particles and microbubbles: Nucleation phenomena at solid surfaces.

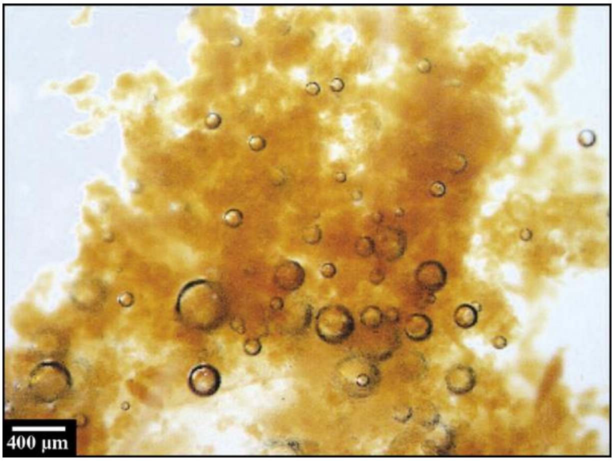


Figure 4.5 Mechanisms involved in the interaction between particles and microbubbles: Bubbles entrapment or physical trapping inside the flocs or aerated flocs formation

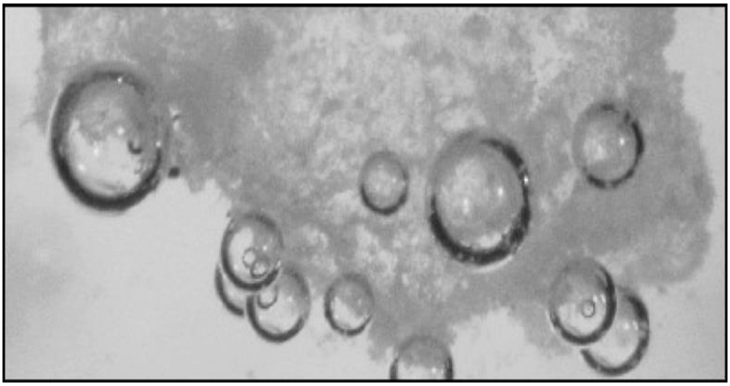


Figure 4.6 Mechanisms involved in the interaction between particles and microbubbles: Aggregates entrainment, by the rising bubbles ("cloud")

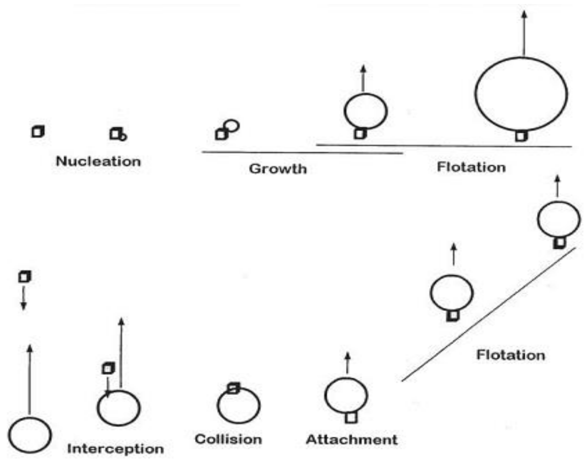


Figure 4.7 Schematic diagram of flotation process

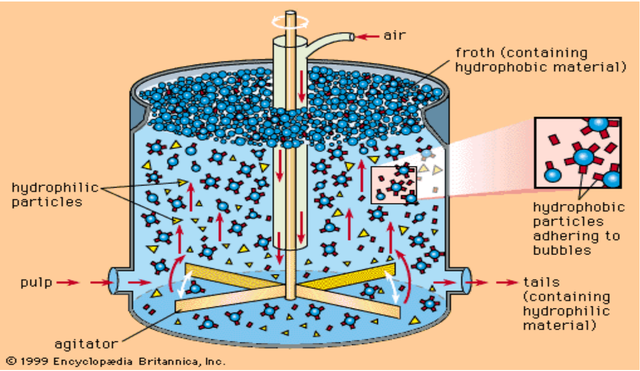


Figure 4.8 Visualization of flotation process

Flotation is especially useful to separate very small particles or light particles with low settling velocities. In such cases more complete and rapid separation can be obtained with flotation than with sedimentation

Chemical Additives to Enhance Flotation Processes

Chemical additives that promote the attachment or entrapment of air bubbles to solid particles or flocs can be effectively used to enhance flotation.

Collectors

Collectors either chemically bond (chemisorption) on a hydrophobic mineral surface, or adsorb onto the surface in the case of, for example, coal flotation through physisorption. Collectors increase the natural hydrophobicity of the surface, increasing the separability of the hydrophobic and hydrophilic particles.

- Xanthates
- Potassium Amyl Xanthate (PAX)
- Potassium Isobutyl Xanthate (PIBX)
- Potassium Ethyl Xanthate (KEX)
- Sodium Isobutyl Xanthate (SIBX)
- Sodium Isopropyl Xanthate (SIPX)
- Sodium Ethyl Xanthate (SEX)
- Dithiophosphates
- Thiocarbamates

- Xanthogen Formates
- Thionocarbamates
- Thiocarbanilide

Frothers

Frothers produces stable bubbles for hydrophobic particles to attach to. Work in liquid phase only and not to mineral surface. It should have low collecting power. Reduce surface tension of the water.

- Pine oil
- Alcohols (MIBC)
- Polyglycols
- Polyoxyparafins
- Cresylic Acid (Xylenol)

Modifiers

Modifiers as activators, depressants or pH modifiers. Alters selectivity of the collectors. It intensifies or reduces their water repellent effect on the mineral surface. Activator-soluble salts which ionizes in solution E.g. activation of sphalerite by Cu in solution. Depressant are used to increase the selectivity of floatation by rendering certain minerals hydrophilic thus preventing their floatation.

Cationic modifiers: Ba^{2+}, Ca^{2+}, Cu^{+}, Pb^{2+}, Zn^{2+}, Ag^{+}

Anionic modifiers: SiO_3^{2-}, PO_4^{3-}, CN^{-}, CO_3^{2-}, S^{2-}

Organic modifiers: Dextrin, starch, glue, CMC pH modifier floatation is carried out at alkali pH because most collector are stable at higher pH & corrosion of cells, pipework is minimized.

pH modifiers such as:

- Lime CaO
- Soda ash Na_2CO_3
- Caustic soda NaOH
- Acid H_2SO_4, HCl

Characterization of Flotation Separations

Flotation requires the generation of small bubbles which can be produced by:

- dispersing air into the suspension
- applying a vacuum to the suspension
- dissolving air into pressurized suspension and then releasing the pressure

Dispersed Air Flotation

Air bubbles are formed by mechanically dispersing air injected under rotating impellers or sparged by diffusers. The bubbles formed under these conditions are typically too coarse for fine solid removal. Hence this method is not commonly encountered. Some scum forming waste can be removed by air dispersion flotation

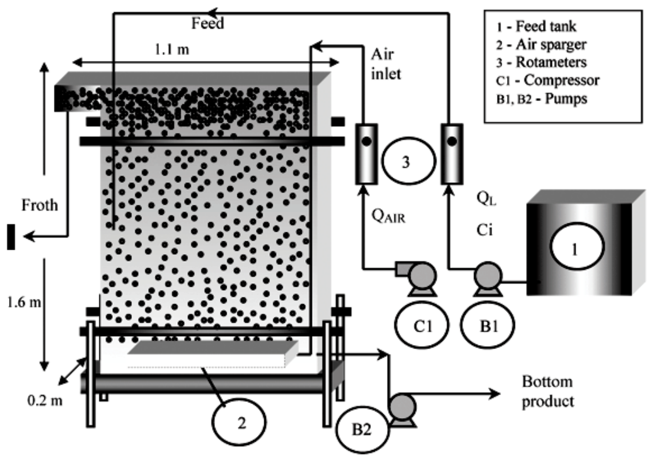


Figure 4.9 Schematic of laboratory scale dispersed air flotation

Vacuum Flotation

- Air is first dispersed into the feed to achieve saturation conditions
- Partial vacuum is then applied to the feed. This results in the generation of small air bubbles that attach themselves to the solid particles and make them rise
- Because there is a maximum of 1 atm pressure difference there is a severe limitation on the amount of air available for flotation. This limits the applicability of this process.

Dissolved Air Flotation

- Pressurized air (40- 95 psia, i.e., 275 - 650 kPa) is dissolved in feed by adding air to the pump suction point
- The air-feed mixture is admitted to a retention tank having a residence time or a few minutes to allow the air to dissolve

- The wastewater passes through a pressure reducing valve and then enters a flotation unit where small bubbles (30 - 120 mm) are generated within the bulk of the wastewater

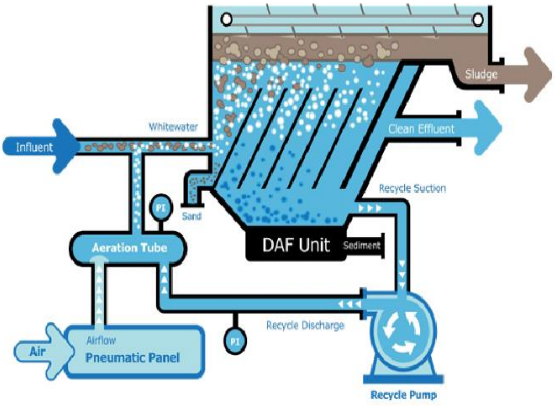


Figure 4.10 Dissolved Air Flotation

Flotation equipment: conventional flotation techniques, devices and processes

<u>Electro Flotation (EF)</u>

The basis for the micro-bubble's generation is the electrolysis of diluted aqueous, conducting solutions with the production of gas bubbles at both electrodes. Tiny bubbles of hydrogen and oxygen gases generated from water electrolysis. Applications, to date, at an industrial scale, have been in the area of removal of light colloidal systems such as emulsified oil from water, ions, pigments, ink and fibers from water.


Figure 4.11 Electro Flotation (EF)

Dispersed (induced) air flotation (IAF)

Bubbles are mechanically formed by a combination of a high-speed mechanical agitator and an air injection system. The technology makes use of the centrifugal force developed. The gas, introduced at the top, and the liquid become fully intermingled and, after passing through a disperser outside the impeller, form a multitude of bubbles sizing from 700–1500 lm diameter. This method, well known in mineral processing, is utilized also in the petrochemical industry, for oil–water separation (oily sewage).

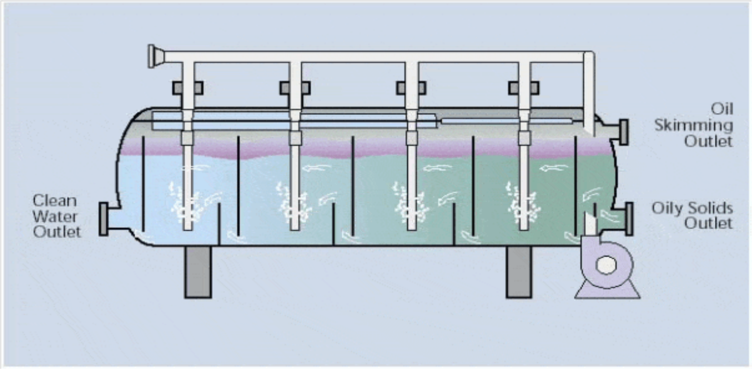
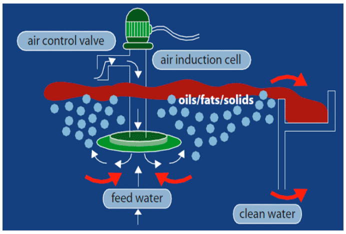


Figure 4.12 Dispersed (induced) air flotation (IAF)



The unit consists of:

- a flotation tank
- a vertically mounted aerator
- a circular sludge skimmer or chain sludge scraper

Figure 4.13 Industrial scale of dispersed (induced) air flotation (IAF)

Dissolved Air (Pressure) Flotation (DAF)

Bubbles are formed by a reduction in pressure of water pre-saturated with air at pressures higher than atmospheric. The supersaturated water is forced trough needle-valves or special orifices, and clouds of bubbles, 30–100 μm in diameter, are produced just down-stream of the constriction.

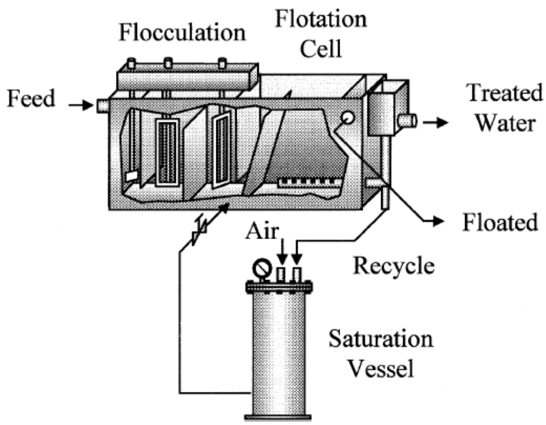


Figure 4.14 Dissolved Air (Pressure) Flotation (DAF)

DAF was recognized as a method of separating particles in the early 20th century and since then has found many applications including:

- clarification of refinery wastewater, wastewater reclamation,
- separation of solids and other in drinking water treatment plants;
- sludge thickening and separation of biological flocs;

Emerging Flotation Techniques and Processes

Nozzle Flotation (NF)

This process uses a gas aspiration nozzle (an eductor or an exhauster) to draw air into recycled water, which in turn is discharged into a flotation vessel (similar to the dispersed-air conventional machines), to develop a two phases mixture of air and water. Bubbles are of the size 400–800 μm in diameter. Advantages claimed for the nozzle units, over induced air flotation (IAF) systems, are the following:

- lower initial costs and energy use because a single pump provides the mixing and air supply;
- lower maintenance and longer equipment life because the unit has no high-speed moving parts to wear out.

Applications reported have been exclusively in the petrochemical industry for the separation of o/w emulsions and treatment of oily metal-laden wastewater

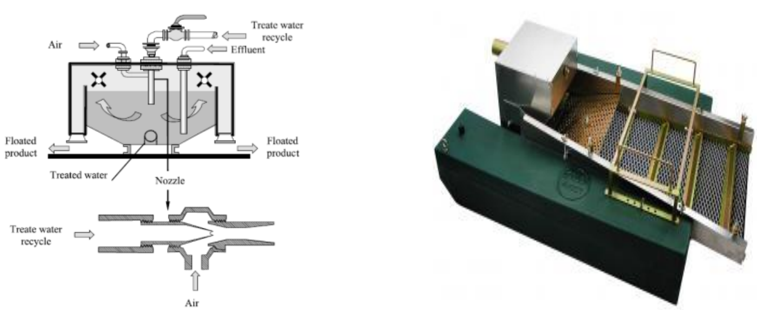


Figure 4.15 Nozzle Flotation (NF)

Column Flotation

Column flotation is still a subject of great interest in mineral processing with a steadily growing number of research studies and industrial applications. In the columns used in the mineral processing area, feed slurry enters about one-third the way down from the top and descends against a rising swarm of bubbles generated by a sparger. In wastewater treatment, feed enters by the column top in the middle of the ‘‘concentrate’’ product. New developments in column technology include external gas spargers operating with and without addition of surfactant or frothers, columns with internal baffles and coalescers for oil recovery. Applications of column flotation in the field of oil removal in production waters and in the recovery of heavy metals precipitates.

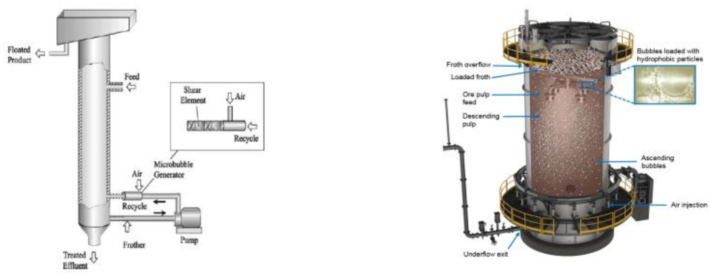


Figure 4.16 Column Flotation

Centrifugal Flotation (CF)

The separator and contactor can be an hydro cyclone or a simple cylinder. Thus, a centrifugal field is developed. Aeration occurs by either injecting air (or by suction), through flow constrictions, such as static mixers or nozzles, medium size bubbles having 100–1000 µm diameters are generated.

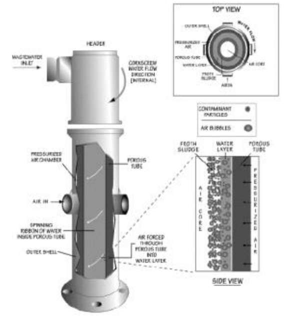


Figure 4.17 Centrifugal Flotation (CF)

Cavitation Air Flotation (CAF)

Cavitation air flotation utilizes an aerator (rotating disc), which draws ambient air down a shaft and injects ‘‘micro-bubbles’’ directly into the feed. However, there is no knowledge of any fundamental work with this flotation technique. CAF is utilized in the food industry, especially in the milk industry, paint and tanneries to remove suspended solids, fats, oils, greases, BOD (biological oxygen demand) and COD (chemical oxygen demand).

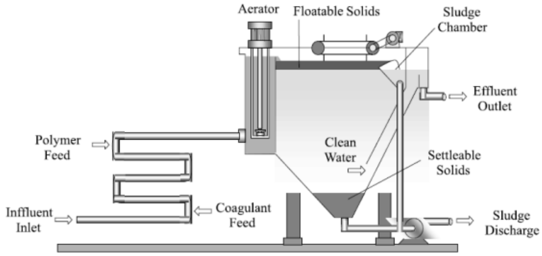


Figure 4.18 Cavitation Air Flotation (CAF)

Application

Flotation process is a method of separation widely used in the wastewater treatment and mineral processing industries.

Recent development:

- analytical chemistry;
- protein separation;
- treatment of spent photography liquors;
- odor removal;
- plastics separation and recycling;
- harvesting or removal of algae;

- deinking of printed paper;
- separation or harvesting of micro-organisms;
- removal of sulfur dyes, seed hulls, serum, resins and
- rubber, impurities in cane sugar; and
- clarification of fruit juices.

Microorganism; It has been demonstrated, for many years, that bacteria can be readily concentrated by froth or foam flotation and since that time a number of investigators have confirmed not only the flotation of bacteria, but of algae and other micro-organisms).

Proteins: Various other non-fatty organic materials, such as soluble proteins derived from soybean processing, can be removed from water by DAF flotation after precipitation and flocculation. The basis for protein separation by flotation is the aggregation of the macromolecules with inorganic salts and/or polymers and flotation with micro-bubbles.

Plastics; Most of the commonly used plastics, such as polyvinyl chloride, polycarbonates, polyacetal, and polypropylene ether are naturally hydrophobic and are readily floated without addition of a flotation collector. Thus, process selectivity is a difficult task. However, plastics vary in their hydrophobicity's and their critical surface tensions have been explored using surface-active reagents. Thus, their float abilities can be modulated by use of suitable depressants, which include sodium lignin sulfonate, tannic acid.

Deinking; Flotation has been used, for a number of years, in paper deinking for paper recycling. Most of the studies are based on ink removal using surfactants and calcium bearing salts.

2.2 Exercise

Works in a group and analyse the advantages and disadvantages of various flotation system.

3. End of Chapter 4

3.1 Summary

Flotation is a separation process based on the use of very fine gas bubbles that attach themselves to the solid particles in suspension to make them buoyant and drive them toward the free surface of the liquid. Chemical additives that promote the attachment or entrapment of air bubbles to solid particles or flocs can be effectively used to enhance flotation can be added such as collectors, frothers and modifiers. The selection of flotation type is dependent on the objectives of the process.

3.2 Exam

How does a dissolved air flotation work?

3.3 Feedback

Successful completion of this chapter is measured by the ability of students to explain the principles of flotation, application and various flotation process system.

3.4 Following action

Students may do some more reading on the flotation chapter in the reference book. After that, students can continue to read the following chapters.

3.5 Solution

DAF is a flotation system with pressurized air (40- 95 psia, i.e., 275 - 650 kPa) is dissolved in feed by adding air to the pump suction point. The air-feed mixture is admitted to a retention tank having a residence time or a few minutes to allow the air to dissolve. The wastewater passes through a pressure reducing valve and then enters a flotation unit where small bubbles (30 - 120 mm) are generated within the bulk of the wastewater

References

1 Brown, G.G., Kate, D., Foust, A.S., and Schneidewind, R. 1950. Unit Operations. New York: Jhon Wiley & Sons, Inc.

2 Green, D.W. and Maloney, J.O. 1997. Perry's Chemical Engineers Handbook. USA: Mc Graw Hill Ltd.

Glossary

Dissolved Air Flotation is a flotation system with pressurized air (40- 95 psia, i.e., 275 - 650 kPa) is dissolved in feed by adding air to the pump suction point.

Dispersed (induced) air flotation (IAF) is a flotation system with a combination of a high-speed mechanical agitator for bubbles generation and an air injection system

CHAPTER 5
SEDIMENTATION

1. Introduction

1.1 Brief Description

This chapter discussed the basic principle of sedimentation, type of sedimentation and sedimentation tank as well as the application of sedimentation process in the industry.

1.2 Relevance

Sedimentation is a common process used in the wastewater treatment and the ability to understand the basic principle of sedimentation, type of sedimentation and sedimentation tank and its application is necessary for the students.

1.3 Learning Outcome

After completing the course students will be able to design (C6) chemical engineering operations units including a complex integrated system consisting of several operating units. In details, students will be able to:

a) explain (C2) the basic concepts and principles of the sedimentation process
b) analyse and evaluate (C4, C5) the design sedimentation tank.

1.4 Learning Instruction

Read the Chapter 5 along with other complementary supplements such as, Unit Operations of Chemical Engineering, by Mc Cabe et al 1993 and Unit Operation by Brown, 1950. Source from the internet also can be added to see the development of sedimentation system. Work on the exercise and quizzes for improve the learning outcome achievements.

2. Materials

2.1 Materials Description

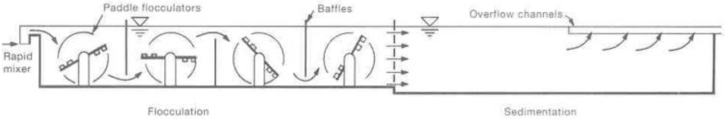
Definition

Sedimentation is the process of allowing particles in suspension in water to settle out of the suspension under the effect of gravity. The particles that settle out from the suspension become sediment, and in water treatment is known as sludge. When a thick layer of sediment continues to settle, this is known as consolidation. When consolidation of sediment, or sludge, is assisted by mechanical means then this is known as thickening. Sedimentation is the oldest form of water treatment that uses gravity to separate particles from water and it often follows coagulation and flocculation.

Figure 5.1 Sedimentation system in industrial plant

Settling- a unit operation in which solids are drawn toward a source of attraction. The particular type of settling that will be discussed in this section is gravitational settling. It should be noted that settling is different from sedimentation.

Sedimentation- The condition whereby the solids are already at the bottom and in the process of sedimenting. Settling is not yet sedimenting, but the particles are falling down the water column in response to gravity. Of course, as soon as the solids reach the bottom, they begin sedimenting. In the physical treatment of water and wastewater, settling is normally carried out in settling or sedimentation basins.



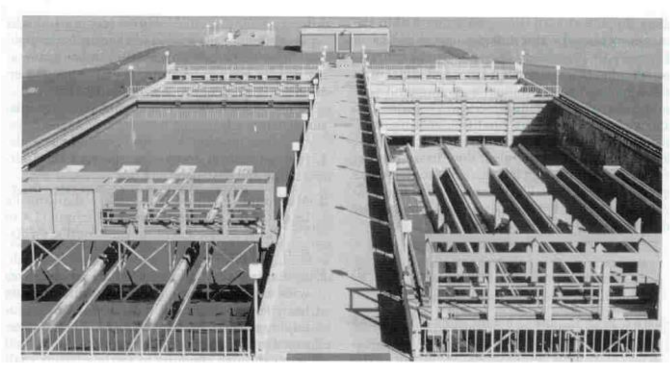


Figure 5.2 Integrated sedimentation system in industrial plant

Sedimentation: Effect of the particle concentration

Dilute suspensions

- Particles act independently

Concentrated suspensions

- Particle-particle interactions are significant
- Particles may collide and stick together (form flocs)
- Particle flocs may settle more quickly
- At very high concentrations particle-particle forces may prevent further consolidation

Types of settling followed by sedimentation:

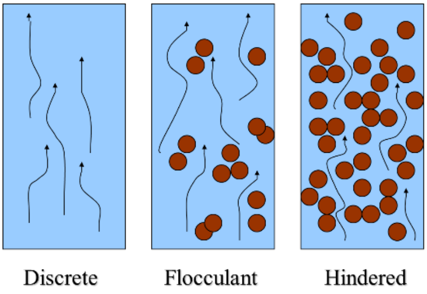


Figure 5.3 Types of Settling followed by sedimentation

Type of Sedimentation

Type 1 sedimentation

- particles concentration is very low
- settle as individual particles
- example: sand and grit material removal in wastewater treatment process

Type 2 sedimentation

- particles concentration is low
- particles flocculate during settling
- example: particles removal in sedimentation tank

Type 3 sedimentation / zone sedimentation

- particles concentration is high
- particles tend to settle as a mass and form a layer called "blanket"
- distinct clear zone and sludge zone are present
- example: secondary sedimentation in wastewater treatment plant

Settling velocity follows Stoke's Law:

$$V_s = \frac{g(\rho_p - \rho)D_p^2}{18\mu}$$

v_s = particle settling velocity (m/s or ft/s)

ρ_p = particle density (kg/m^3 or lb_m/ft^3)

ρ = fluid density (kg/m^3 or lb_m/ft^3)

d = particle diameter (m or ft)

g = gravitational acceleration (9.81 m/s^2 or 32.2 ft/s^2)

μ = dynamic viscosity (kg/m·s or lb$_m$/ft·s)

Denser and large particles have a higher settling velocity

- $N_{Re} < 1$: laminar flow; $C_D = 24/N_{Re}$

$$V_S = \frac{g}{18\mu}(\rho_S - \rho)d^2$$ Stokes equation

- $1 < N_{Re} < 10^4$: transition flow; $C_D = \frac{24}{N_{Re}} + \frac{3}{\sqrt{N_{Re}}} + 0.34$

- $N_{Re} > 10^4$: turbulent flow; $C_D = 0.4$

$$V_S = \sqrt{3.3g(S_s - 1)d}$$ Newton equation

What are the factors that affects sedimentation?

- Detention time
- Velocity
- Surface turbulence
- Short circuits
- Temperature
- Inlet and outlet

Type of Sedimentation Tank

1. Based on methods of operation
    - Fill and draw type tank
    - Continuous flow type tank
2. Based on shape
    - Circular tank

- Rectangular tank
- Hopper bottom tank

3. Based on location
   - Primary tank
   - Secondary tank

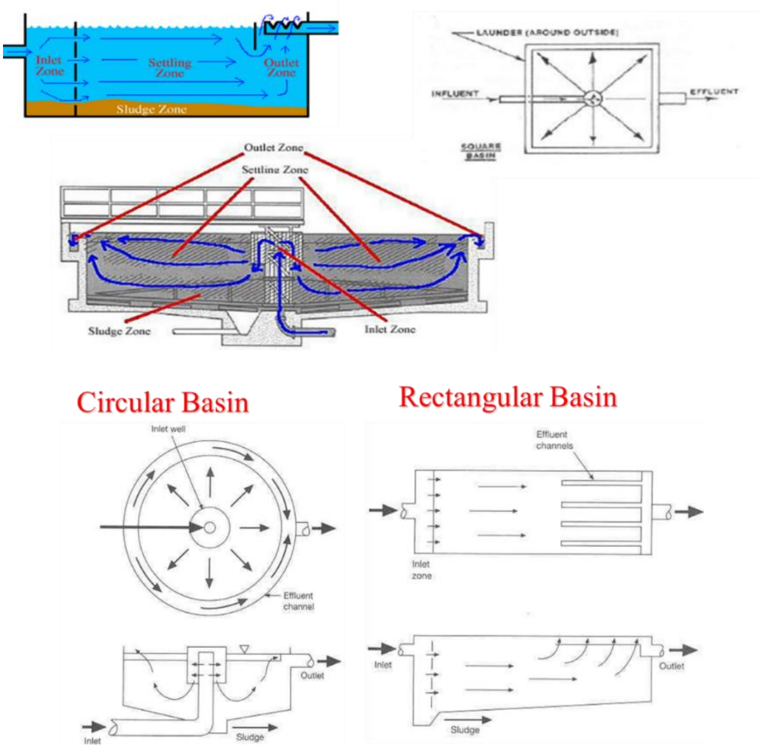


Figure 5.4 Types of sedimentation tank

Geometry of Sedimentation Basin

Selection of shape based on:

- size of installation
- available land and site condition

- Preferences and experience of operators and ‘or design engineers

Advantages of rectangular basin:

- Occupy less space by using common walls
- Less short circuiting due to near plug flow condition
- Less power requirement

Disadvantages of rectangular basins:

- Restricted in width by collection equipment
- Require multiple rows of weirs

Sedimentation tank design:

- Preconditions:

  Specific gravity of the particles should be larger than the fluid
- Two important terms to understand in sedimentation zone design:
  1. The particles (floc) settling velocity
  2. The overflow rate, v or u – the velocity at which the tank is designed to operate

Sedimentation Concepts

υ_s - settling velocity
υ_0 - over flow rate

$$\upsilon_0 = \frac{Q}{As} = \frac{H}{t}$$

Where
Q = flow rate
As = surface area
H = depth of water
t = detention time

If $\upsilon_s > \upsilon_o$, particles will completely settle

If $\upsilon_s < \upsilon_o$, particles do not settle unless the particles are at h level when entering the sedimentation tank, where

$$h = \upsilon_s t$$

To get the effective of sedimentation tank, $\upsilon_o <<< \upsilon_s$. This can be achieved by increasing
the area of the tank ($\upsilon_o = Q/As$)

Application

Sedimentation can be applied in the Pre-sedimentation of river water with high suspended solids, Sedimentation after coagulation and flocculation, Sedimentation for recovery of filter backwash waste or Sedimentation for gravity thickening of sludge.

Figure 5.5 Sedimentation for gravity thickening of sludge

2.2 Exercise

A water treatment plant has a flow rate of 0.6 m3/sec. The settling basin at the plant has an effective settling volume that is 20 m long, 3 m tall and 6 m wide. Will particles that have a settling velocity of 0.004 m/sec be completely removed? If not, what percent of the particles will be removed?

3. End of Chapter 5

3.1 Summary

Sedimentation is the process of allowing particles in suspension in water to settle out of the suspension under the effect of gravity. The particles that settle out from the suspension become sediment, and in water treatment is known as sludge. Two important functions of these sedimentation tanks are: clarification and thickening. Two important terms to understand in sedimentation zone design the particles (floc) settling velocity (υ_s) and the overflow rate (υ_o) the velocity at which the tank is designed to operate

3.2 Exam

Explain the correlation between settling velocity and overflow rate!

3.3 Feedback

Successful completion of this chapter is measured by the ability of students to explain the principles of sedimentation and application as well as conducting assessment for sedimentation selection and calculation.

3.4 Following action

Students may do some more reading on the sedimentation chapter in the reference book and many other sedimentations paper available on the internet.

3.5 Solution

The correlation between settling velocity (υ_s) and overflow rate (υ_o) can be explain with comparing their value.

If $\upsilon_s > \upsilon_o$, particles will completely settle

If $\upsilon_s < \upsilon_o$, particles do not settle unless the particles are at h level when entering the sedimentation tank, where $h = \upsilon_s t$

For effective of sedimentation tank, $\upsilon_o <<< \upsilon_s$. This can be achieved by increasing

the area of the tank ($\upsilon_o = Q/As$)

References

1. Brown, G.G., Kate, D., Foust, A.S., and Schneidewind, R. 1950. Unit Operations. New York: Jhon Wiley & Sons, Inc.
2. Darby, R. 1932. Chemical Engineering Fluid Mechanics. New York: Marcel Dekker.
3. Green, D.W. and Maloney, J.O. 1997. Perry's Chemical Engineers Handbook. USA: Mc Graw Hill Ltd.

Glossary

Stoke’s Law is mathematical equation that expresses the drag force resisting the fall of small spherical particles through a fluid medium.

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Dessy Ariyanti is a lecturer in the Department of Chemical Engineering, the Faculty of Engineering, Universitas Diponegoro. She holds doctoral degree in Chemical and Material Engineering from the University of Auckland, New Zealand. Her research focuses on the development of advanced materials for water and wastewater treatment, smart material application, renewable energy, and energy storage system. She is a researcher in Center of Biomass and Renewable Energy as well as in Advanced Material Laboratory in Universitas Diponegoro and involved in the SDGs Center Universitas Diponegoro. She is also a member of The American Institute of Chemical Engineers and expert consultant for several company.

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