



CHAPTER II

THEORY

Theory of seven selected experimental units are briefly explained in this chapter.

2.1 Filtration

Filtration is an operation used for separating solid particles from a fluid. It can be worked by passing the fluid through filtering medium forced by pressure. The solid particles remaining on filter media are called “cake” and the clear liquid passing the filter media is called “filtrate”.

There are several types of filtering process used in industry. They are either continuous or batch processes, depending on whether the discharge of filtered solid is steady or intermittent. Plate-and-Frame filter press is selected to represent this unit in this work. This filter consists of plates and frames assembled alternatively with filter cloth over each side of the plates. Clear filtrate liquid can drain down along each channels cut in the plates. The solid builds up as a cake on the frame side of the cloth after pump feeds slurry into the press and flows through the filter cloth. The filtration proceeds until the frames are completely filled with solid and liquid no longer flows out.

The flow of filtrate through the filter cake can be described by any of the general equation for flow through packed bed in laminar flow. In this case, the Carman-Kozeny and Blake-Kozeny equation is selected.

$$-\frac{\Delta P_c}{L} = \frac{k_1 \mu v (1 - \epsilon)^2 S_0^2}{\epsilon^3} \quad (2.1-1)$$

where

k_1 = a constant = 4.17 for random particles with specific size and shape

μ = filtrate viscosity (Pa.s)

v = linear velocity depending on filter area (m/sec)

ε = void fraction or cake porosity

L = cake thickness (m)

S_0 = specific surface area of particle

= area of particle(m^2)/volume of particle(m^3)

ΔP_c = pressure drop in cake (N/m^2)

The linear velocity v is given by

$$v = \frac{dV/dt}{A} \quad (2.1-2)$$

where

A = the filter area (m^2)

V = volume of filtrate (m^3) collected from the start of the filtration to time t (sec)

Material balance equation for solid in the system will provide relationship between cake thickness and volume of filtrate.

$$LA(1-\varepsilon)\rho_p = C_s(V + \varepsilon LA) \quad (2.1-3)$$

in which

ρ_p = particle density (kg/m^3)

C_s = slurry concentration = kg of solid/ m^3 of filtrate

εLA is the volume of filtrate that held in filter cake, which is normally infinitesimal comparing with total volume of filtrate (V). Assuming this term negligible and substituting v from equation (2.1-2) and L from equation (2.1-3) into equation (2.1-1) gives

$$\frac{dV}{A dt} = \frac{-\Delta P_c}{\frac{k_1(1-\varepsilon)S_0^2}{\rho_p \varepsilon^3} \cdot \frac{\mu C_s V}{A}} = \frac{-\Delta P_c}{\alpha \frac{\mu C_s V}{A}} \quad (2.1-4)$$

where α is a specific cake resistance, defined as

$$\alpha = \frac{k_1(1-\varepsilon)S_0^2}{\rho_p \varepsilon^3} \quad (2.1-5)$$

A similar equation with equation (2.1-4) is

$$\frac{dV}{A dt} = \frac{-\Delta P_f}{\mu R_m} \quad (2.1-6)$$

in which

R_m = filter medium resistance (m^{-1})

ΔP_f = pressure drop caused by filter media (Pa).

Total pressure drop in this system is the sum of cake resistance and medium resistance.

$$\frac{dV}{A dt} = \frac{-\Delta P}{\mu \left(\frac{\alpha C_s V}{A} + R_m \right)} \quad (2.1-7)$$

when $\Delta P = \Delta P_c + \Delta P_f$.

Equation (2.1-7) can be rearranged to express in term of an equivalent volume of filtrate as follows,

$$\frac{dV}{A dt} = \frac{-\Delta P}{\frac{\mu \alpha C_s}{A} (V + V_e)} \quad (2.1-8)$$

where

V_e = volume of filtrate built in filter cake that have specific resistant R_m .

For a batch filtration process with constant pressure, equation (2.1-7) can be rearranged as

$$\frac{dt}{dV} = \frac{\mu \alpha C_s}{A^2 (-\Delta P)} V + \frac{\mu R_m}{A (-\Delta P)} \quad (2.1-9)$$

or
$$\frac{dt}{dV} = K_p V + B \quad (2.1-10)$$

in which

$$K_p = \frac{\mu \alpha C_s}{A^2 (-\Delta P)} \quad : \text{sec/m}^6 \quad (2.1-11)$$

and
$$B = \frac{\mu R_m}{A(-\Delta P)} \quad : \text{sec/m}^3 \quad (2.1-12)$$

Assuming cake in the system is incompressible ($\alpha = \text{constant}$) and pressure is constant, integrate equation (2.1-10) will provide the filtration time as follows,

$$\int_0^t dt = \int_0^V (K_p V + B) dV \quad (2.1-13)$$

$$t = \frac{K_p}{2} V^2 + BV \quad (2.1-14)$$

Equation (2.1-14) is a basic equation for filtration rate operated batchwise.

In filtration equation, experimental data of time (t) and volume of filtrate (V) is used to find the specific cake resistance. The procedure for finding two constants value is as follows,

- 1) Collecting data between V and t .
- 2) Finding ΔV and Δt , the difference of the near data point and the average filtrate volume, V_{avg} .
- 3) Calculating $\Delta t / \Delta V$
- 4) Plotting $\Delta t / \Delta V$ vs V_{avg} ,

with assuming $\frac{\Delta t}{\Delta V} \cong \frac{dt}{dV}$ in equation (2.1-10).

- 5) Drawing a linear line as shown in figure 2.1-1.

The slope of this linear line is K_p and the intercept is B .

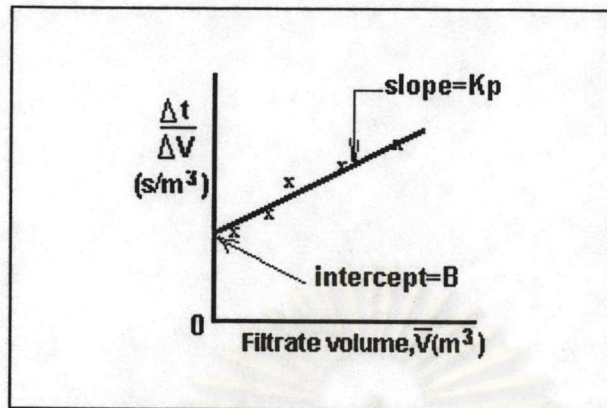


Figure 2.1-1 Graphical example in finding K_p and B constants.

6) Finding α and R_m from equation (2.1-11) and (2.1-12).

2.2 Sedimentation

Sedimentation is also an operation for separating solid out of a fluid by mechanical separation based on the movement of solid particles through a fluid by gravitational force. Product from sedimentation process may be either clear liquid or thicken slurry. If desired product is liquid, this equipment will be called as “clarifier”. When thicken slurry is a desired product, it is called as “thickener”. The progression of batch sedimentation is shown in figure 2.2-1.

The stages occurring in settling process of a flocculated suspension can be observed using a glass cylinder. At first, slurry has uniform concentration of uniform solid particles, zone B. As soon as the process starts, all particles begin to settle causing a zone of clear liquid, zone A, and settled solid, zone D. Above zone D is a transition layer, zone C, in which the solid content varies in size and concentration. Zone B is a uniform-concentration zone and its concentration is equal to the original. It is usually assumed the velocity of particles approaches rapidly the terminal velocity under hindered-settling conditions.

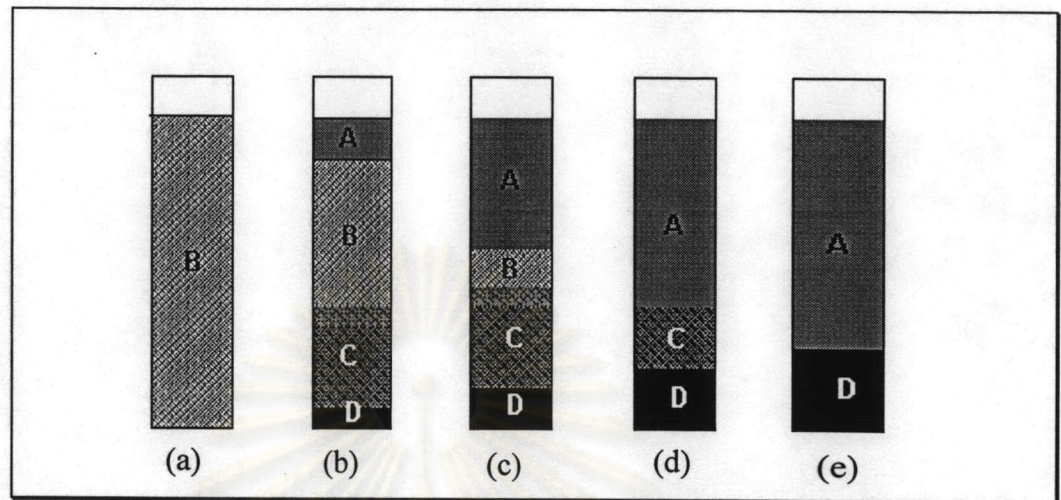


Figure 2.2-1 Batch sedimentation.

As settling continues, the height of each zone varies as shown in figure 2.2-1 (b), (c), and (d). Zones A and D increase in height but zone B decreases and zone C remains nearly constant. Eventually zones B and C disappear and all the solid are in zone D. This point is called “critical settling point” (figure 2.2-1 (e)), the point at which a single distinct interface forms between clear liquid and sediment. After this point, only a slow compression of the solid still take place.

Determination of settling velocity can be made using theory and experimental data.

1) From Theory

1.1) Free settling velocity

Stokes'law can be used to find terminal velocity for a spherical particle that flow in laminar region (Reynolds number of particle is less than 1).

$$v_b = \frac{gD_p^2(\rho_p - \rho)}{18\mu} \quad (2.2-1)$$

where g = gravity acceleration = 9.81 m/s^2

D_p = particle diameter (m)

$$\begin{aligned}\rho_p &= \text{particle density (kg/m}^3\text{)} \\ \rho &= \text{fluid density (kg/m}^3\text{)} \\ \mu &= \text{fluid viscosity (Pa.s)}\end{aligned}$$

1.2) Hindered settling velocity

Hindered settling will occur in high concentration slurry. In this case, one must substitute fluid density and viscosity by bulk density and viscosity of slurry in equation (2.2-1).

$$v_h = \frac{gD_p^2(\rho_p - \rho_b)}{18\mu_b} \quad (2.2-2)$$

where ρ_b, μ_b = bulk density and viscosity of slurry, respectively

Bulk density of slurry can be calculated the following equation

$$\rho_b = \epsilon\rho + (1-\epsilon)\rho_p \quad (2.2-3)$$

where ϵ = volume fraction of fluid in slurry mixture.

Bulk viscosity is a physical property of specify mixture. It can be estimated from reference handbook. Table 2.2-1 show the bulk viscosity of the mixture of Calcium Carbonate in water.

Table 2.2-1 Bulk viscosity of the mixture of CaCO₃ in water.

weight fraction of CaCO ₃ in water (%)	bulk viscosity, μ_b (c.p.)
0	1.00
5	1.11
10	1.37

Another method needs empirical correction factor (R) which depends on the volume fraction of fluid in slurry. The R factor was obtain from figure 2.2-2 or the following equation

$$R = \frac{\epsilon}{10^{1.82(1-\epsilon)}} \quad (2.2-4)$$

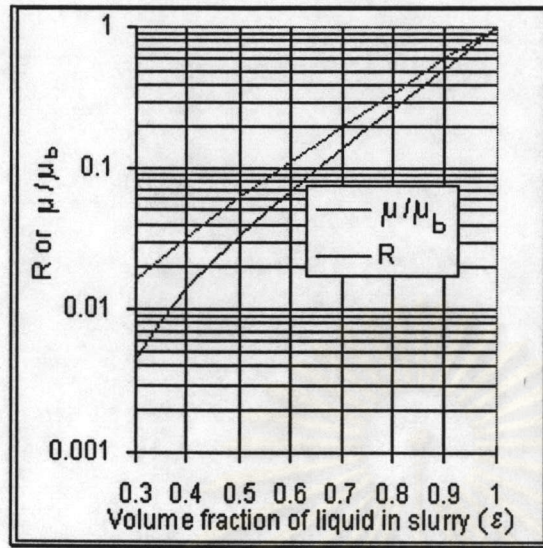


Figure 2.2-2 Settling factor for hindered settling.

The hindered-settling velocity is given by

$$v_m = \frac{(\rho_p - \rho)gD_p^2}{18\mu} R \quad (2.2-5)$$

2) From experimental data

The result of batch sedimentation is shown in figure 2.2-3. The height of interface increases with time rapidly from the beginning to the critical point (C). Slope of this graph is a settling velocity. Terminal velocity is determined from a constant slope at the initial.

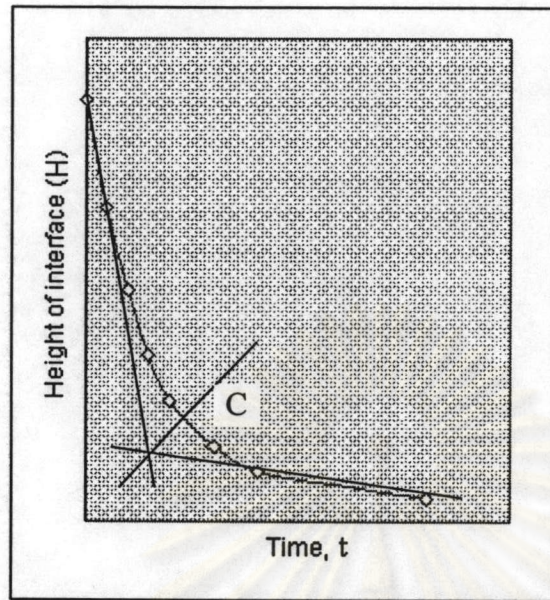


Figure 2.2-3 Graphical analysis of interface settling curve.

2.3 Sieve Analysis

The characterization of solid particle is necessary for design of processes and equipments dealing with solids. Individual solid particles are characterized by their shape, size and density. Screen or Sieve Analysis is one method in measuring particle-size. Standard screens are used to measure the size distribution of particle in the size range between about 76 mm to 38 μm . Standard screens of either the Tyler series or U.S. sieve series are used in industry. Each screen is identified in meshes per inch. For Tyler standard screen series, the set of screens is based on the opening of the 200-mesh screen (0.074 mm). The area of the openings in any one screen in the series is exactly twice that of the openings in the next smaller screen. Then the ratio of the actual mesh dimension of any screen to the next smaller screen is $\sqrt{2}$. Sometimes, intermediate screen is used for closer sizing, each of which has a mesh dimension $\sqrt[4]{2}$ times that of the next smaller screen.

In making screen analysis, testing sieve is nested one above another, so that each screen has openings larger than the one below. A solid pan is put under the

bottom screen. The sample is put onto the top screen and the stack shaken mechanically for a definite time, usually 10 to 20 minutes. When shaking is finished, the sieves are removed and the material held on each of the sieves is collected and weighed.

The result of screen analysis is initially presented tabularly, showing the mass fraction of each screen increment as a function of the mesh size range of the increment. It could be also presented as a graphical results. An example for screen analysis is shown in table 2.3-1.

Table 2.3-1 Result of typical screen analysis.

Size range (Tyler Mesh)	Average Particle Diameter (Dp), in.	Mass Fraction Retained, weight percent
-10+14	0.0555	2
-14+20	0.0394	5
-20+28	0.0280	10
-28+35	0.0198	18
-35+48	0.0140	25
-48+65	0.0099	25
-65	0.0041	15

From this table, it can be presented as a graphical result. Histogram for this screen analysis is illustrated in figure 2.3-1. Fractional-distribution plot, cumulative-distribution plot, and fractional-distribution plot on semilogarithmic coordinate is shown in figure 2.3-2, 2.3-3, and 2.3-4 respectively.

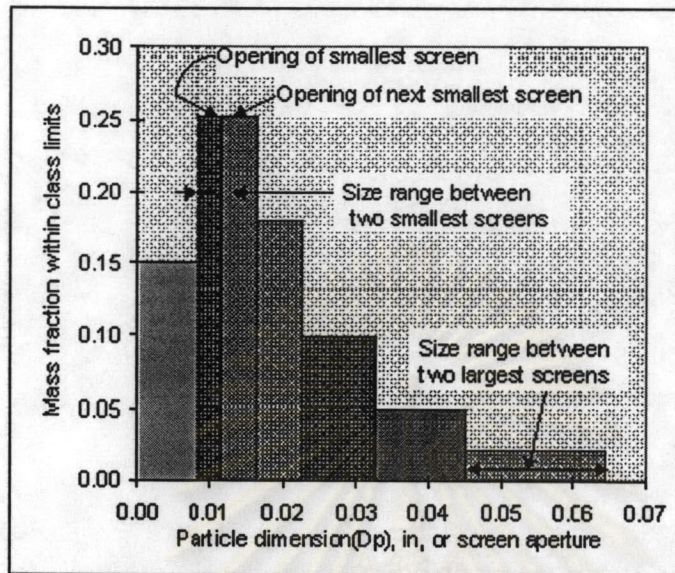


Figure 2.3-1 Histogram for screen analysis in table 2.3-1.

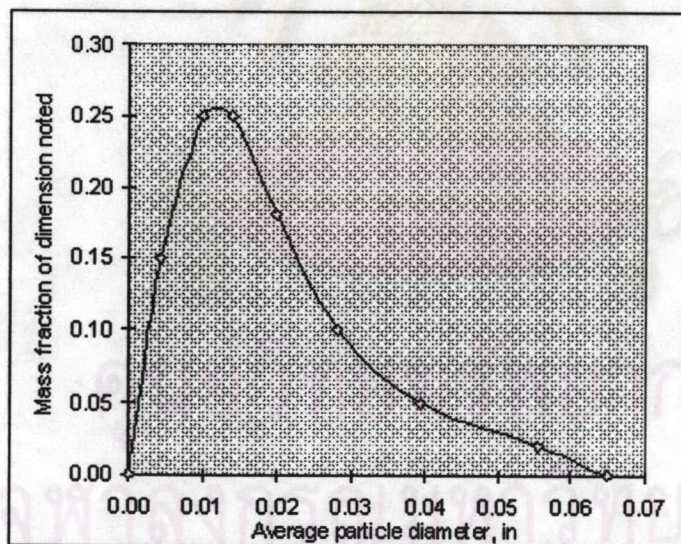


Figure 2.3-2 Fractional-distribution plot for screen analysis in table 2.3-1.

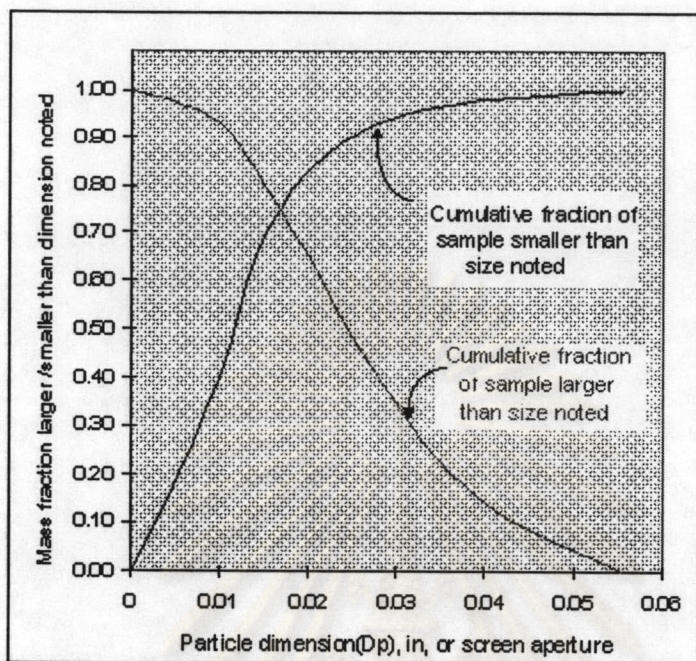


Figure 2.3-3 Cumulative-distribution plot for screen analysis in table 2.3-1.

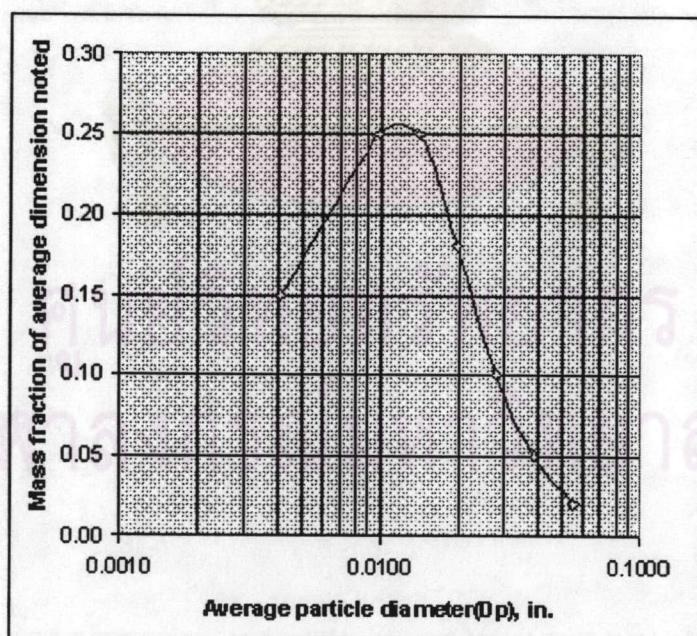


Figure 2.3-4 Fractional-distribution plot for screen analysis in table 2.3-1 in logarithmic coordinate.

The result from screen test is used to determine the characteristic of mixture.

1) Specific surface of mixture (A_w)

If the particle density (ρ_p) and sphericity (Φ_s) are known as a constant, the specific surface or the total surface area of a unit mass of particles is given by

$$A_w = \frac{6x_1}{\Phi_s \rho_p \bar{D}_{p1}} + \frac{6x_2}{\Phi_s \rho_p \bar{D}_{p2}} + \dots + \frac{6x_n}{\Phi_s \rho_p \bar{D}_{pn}} = \frac{6}{\Phi_s \rho_p} \sum_{i=1}^n \frac{x_i}{\bar{D}_{pi}} \quad (2.3-1)$$

where subscripts 1, 2, ... = individual increments

x_i = mass fraction of increment i

n = number of increments

\bar{D}_{pi} = average particle diameter, taken as arithmetic average of smallest and largest particle diameters in increment.

2) Average particle size

The average particle size for a mixture of particle is defined in several different ways as follows,

2.1) Volume-surface mean diameter (\bar{D}_s)

$$\bar{D}_s = \frac{1}{\sum_{i=1}^n (x_i / \bar{D}_{pi})} \quad (2.3-2)$$

2.2) Arithmetic mean diameter (\bar{D}_N)

$$\bar{D}_N = \frac{\sum_{i=1}^n (N_i \bar{D}_{pi})}{N_T} \quad (2.3-3)$$

where N_i = the number of particles in increment i.

N_T = the number of particles in the entire sample.

2.3) Mass mean diameter (\bar{D}_w)

$$\bar{D}_w = \sum_{i=1}^n x_i \bar{D}_{pi} \quad (2.3-4)$$

2.4) Volume mean diameter (\bar{D}_v)

$$\bar{D}_v = \left[\frac{1}{\sum_{i=1}^n (x_i / \bar{D}_{pi}^3)} \right]^{1/3} \quad (2.3-5)$$

3) Number of particles in mixture (N_w)

Providing that the volume shape factor (a) is independent of size, N_w is defined by the equation

$$N_w = \frac{1}{a\rho_p} \sum_{i=1}^n \frac{x_i}{\bar{D}_{pi}^3} = \frac{1}{a\rho_p \bar{D}_v^3} \quad (2.3-6)$$

and the number of particles in each increment is defined as

$$N_i = \frac{x_i}{a\rho_p \bar{D}_{pi}^3} \quad (2.3-7)$$

where a = volume shape factor
 ρ_p = particle density.

2.4 Efflux Time of a Tank

One of the most important batch process in chemical process is transferring liquid from a storage tank. Efflux time is time required to drain liquid from a tank. This unsteady flow problem is solve by using the macroscopic balances of the system as shown in figure 2.4-1.

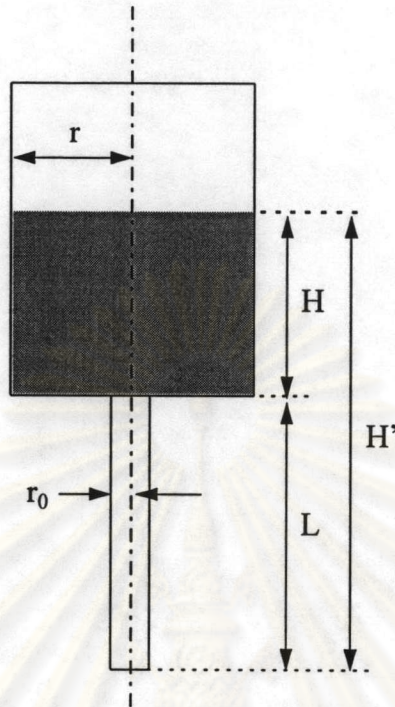


Figure 2.4-1 Tank with long pipe attached, fluid surface and pipe exit are open to atmosphere.

To simplify this operation, the following assumptions should be applied:

- The density (ρ) and viscosity (μ) are constant.
- The fluid in the tank is Newtonian fluid.
- There is no energy lost due to sudden change of cross-section area.
- The kinetic energy of the emerging stream can be neglected.

From Mechanical energy balance with those assumptions, it gives

$$\bar{u} = \frac{gr_0(L + H)}{Lf} \quad (2.4-1)$$

where \bar{u} = average velocity of fluid (m/s)
 f = friction factor

Friction factor, which is a function of Reynolds number (N_{Re}) is defined as

$$f = \frac{16}{N_{Re}} \quad : \text{ for laminar flow} \quad (2.4-2)$$

$$(N_{Re} < 2100)$$

and
$$f = \frac{0.0791}{N_{Re}^{0.25}} \quad : \text{ for turbulent flow} \quad (2.4-3)$$

$$(4000 < N_{Re} < 10^5)$$

Substituting f in equation (2.4-1) gives

$$\bar{u} = \frac{\rho g r_0^2 (L + H)}{8\mu L} \quad : \text{ for laminar flow} \quad (2.4-4)$$

and
$$\bar{u} = \frac{2^{1/7} (L + H)^{4/7} r_0^{5/7} g^{4/7} \rho^{1/7}}{(0.0791)^{4/7} L^{4/7} \mu^{1/7}} \quad : \text{ for turbulent flow} \quad (2.4-5)$$

Mass balance on this system :

Mass out = Mass lost by the system

$$\rho \bar{u} S_0 = -\rho S \frac{dH}{dt} \quad (2.4-6)$$

$$\bar{u} = -\left(\frac{S}{S_0}\right)^2 \frac{dH}{dt}$$

$$\bar{u} = -\left(\frac{r}{r_0}\right)^2 \frac{dH}{dt} \quad (2.4-7)$$

where S and S_0 are cross-section area of tank and pipe respectively.

When \bar{u} is substituted with equation (2.4-4) for laminar flow and with equation (2.4-5) for turbulent flow, the obtained equations are then integrated to give equations used for finding the efflux time of a tank.

- For laminar flow :

$$t_{\text{efflux}} = \frac{8\mu L r^2}{\rho g r_0^4} \ln \left[\frac{(L + H_1)}{(L + H_2)} \right] \quad (2.4-8)$$

- For turbulent flow :

$$t_{\text{efflux}} = K[(L + H_1)^{3/7} - (L + H_2)^{3/7}] \quad (2.4-9)$$

when
$$K = \frac{7}{3} \left(\frac{r}{r_0} \right)^2 \left(\frac{0.0791 L \mu^{1/4}}{2^{1/4} g \rho^{1/4} r_0^{5/4}} \right)^{4/7} \quad (2.4-10)$$

When all fitting equipments are installed, the equations above will be changed by substituting L with total equivalent length of the pipe exit, L_e and substitute (L+H) with the distance from the end of pipe to liquid surface, H' .

- For laminar flow:

$$t_{\text{efflux}} = \frac{8\mu L_e r^2}{\rho g r_0^4} \ln \left[\frac{H'_1}{H'_2} \right] \quad (2.4-11)$$

- For turbulent flow:

$$t_{\text{efflux}} = K[H'_1{}^{3/7} - H'_2{}^{3/7}] \quad (2.4-12)$$

when
$$K = \frac{7}{3} \left(\frac{r}{r_0} \right)^2 \left(\frac{0.0791 L_e \mu^{1/4}}{2^{1/4} g \rho^{1/4} r_0^{5/4}} \right)^{4/7} \quad (2.4-13)$$

2.5 Flow in Pipe

Flow in pipe is the most important phenomenon that provides the information on the operating condition in a plant. The methods for finding velocity distribution of fluid in a cylindrical pipe both in laminar and turbulent flow are described here.

Laminar flow of fluid in a cylindrical pipe may be analyzed by the momentum balance with the following assumptions.

- The fluid has a constant density and viscosity.
- The fluid is Newtonian fluid.
- There is no end effect.

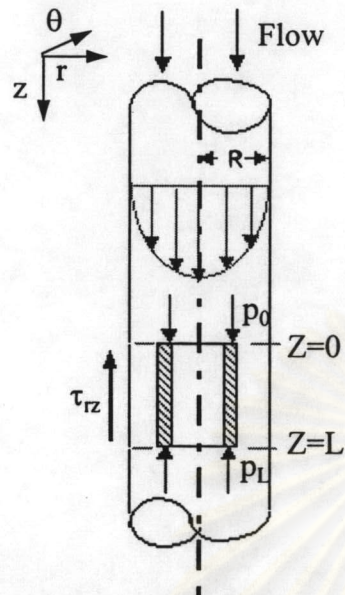


Figure 2.5-1 Cylindrical shell of fluid over which momentum balance is made to get the velocity profile.

The momentum balance in z-direction for a cylindrical shell thickness Δr and length L was set up.

$$(2\pi r L \tau_{rz})|_r - (2\pi r L \tau_{rz})|_{r+\Delta r} + (2\pi r \Delta r \rho u^2)|_{z=0} - (2\pi r \Delta r \rho u^2)|_{z=L} + 2\pi r \Delta r L \rho g + 2\pi r \Delta r (p_0 - p_L) = 0 \quad (2.5-1)$$

Because of assuming the incompressible fluid, u is the same at $z=0$ and $z=L$, hence the third and fourth term are cancellation. Dividing equation (2.5-1) by $2\pi r L \Delta r$ and taking the limit as Δr goes to zero; this gives

$$\lim_{\Delta r \rightarrow 0} \left[\frac{(r\tau_{rz})|_{r+\Delta r} - (r\tau_{rz})|_r}{\Delta r} \right] = \left[\frac{p_0 - p_L}{L} + \rho g \right] r \quad (2.5-2)$$

The left side of equation (2.5-2) can be replaced by the first derivative. Hence this equation may be written as

$$\frac{d}{dr} (r\tau_{rz}) = \left(\frac{p_0 - p_L}{L} \right) r \quad (2.5-3)$$

in which $P = p - \rho gz$. The above equation represents the combined effect of static pressure and gravitational force. For the system that using the horizontal pipe, the height (z) equal to zero therefore $P=p$. Integrate equation (2.5-3) with the boundary condition that define momentum flux is not be infinite at $r=0$. Hence the momentum flux distribution is

$$\tau_{rz} = \left(\frac{P_0 - P_L}{2L} \right) r \quad (2.5-4)$$

According to Newtonian fluid assumption, Newton's law of viscosity can be applied in this system.

$$\tau_{rz} = -\mu \frac{du}{dr} \quad (2.5-5)$$

Substituting equation (2.5-5) into equation (2.5-4) gives the differential equation of the velocity as

$$\frac{du}{dr} = -\left(\frac{P_0 - P_L}{2\mu L} \right) r \quad (2.5-6)$$

Integrating equation (2.5-6) with boundary condition of $u=0$ at $r=R$, provides the velocity distribution as

$$u = \frac{(P_0 - P_L)R^2}{4\mu L} \left[1 - \left(\frac{r}{R} \right)^2 \right] \quad (2.5-7)$$

The average velocity is calculated from the velocity profile in equation (2.5-7).

$$\bar{u} = \frac{\int_0^{2\pi R} \int_0^R u r dr d\theta}{\int_0^{2\pi R} \int_0^R r dr d\theta} = \frac{(P_0 - P_L)R^2}{8\mu L} \quad (2.5-8)$$

Hence the velocity distribution is also a function of average velocity that is the measurable property.

$$u(r) = 2\bar{u} \left[1 - \left(\frac{r}{R} \right)^2 \right] \quad (2.5-9)$$

However, in turbulent flow, the velocity profile equation cannot be derived directly but there is an empirical formula proposed as follows,

$$u(r) = \frac{5}{4} \bar{u} \left[1 - \frac{r}{R} \right]^{1/7} \quad (2.5-10)$$

Estimation of average velocity can be carried out using pitot tube to measure pressure profile in the pipe.

$$u(r) = \sqrt{2gh} \quad (2.5-11)$$

in which
$$h = \frac{(\rho_H - \rho_L)H}{\rho_L} \quad (2.5-12)$$

where ρ_H = density of working liquid used in a manometer (kg/m^3)

ρ_L = density of the fluid flowing in the pipe (kg/m^3)

H = the height difference of working liquid used in a manometer (m).

2.6 Fluidization

Fluidization is a process that solid particles are suspended in gas or liquid flowing with velocity which is higher than a certain value called minimum fluidization velocity. Fluidized beds are used in many catalytic reaction processes, such as the synthesis of acrylonitrile. It is also used for roasting ores, drying fine solids, adsorption of gases and carrying out solid-gas reaction.

The chief advantage of fluidization is rapid and thorough mixing of the solid of therefore it can be assumed that there is no temperature gradient in the bed. It also gives high heat and mass transfer rate in the bed. Because of fluidlike behavior, the solid can be transported easily from a vessel to another one.

Fluidization can be observed in a vertical tube partly filled with a fine granular solid. At the bottom of the tube has a porous plate serving as a distributor. Air flows through the distributor and passes upward into the bed. As the air velocity is increased, the particles will start to move and then become suspended in the air stream, altogether with an increase of pressure drop along the bed. The pressure drop along the bed and the bed height are changed with an increase of the air superficial velocity as shown in figure 2.6-1.

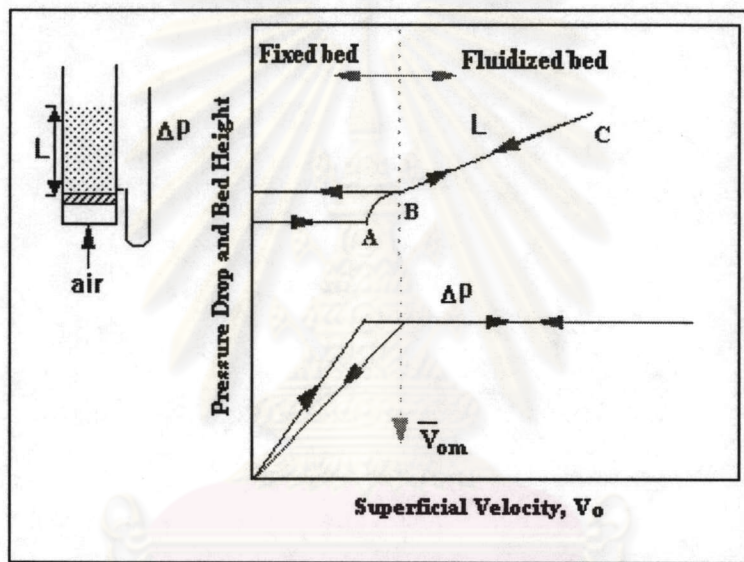


Figure 2.6-1 The relation between pressure drop and bed height with superficial velocity for a bed of solid.

At the initial state, the pressure drop increases with the increase in the air velocity, but the bed height does not change. At point A, the pressure drop across the bed counterbalances the force of gravity on particles or the weight of the bed, and any further increase in velocity will cause the movement of particles. Sometime the bed may expand slightly with constant pressure drop when the air velocity is increased. With a further increase in the air velocity, the particles start to move in the bed, until point B true fluidization begins. The velocity at this point is called “minimum fluidization velocity”. After this point, the pressure drop across the bed becomes constant, but the bed height continues to increase with an increase in the air flow rate.

If the air flow rate is further increased to the terminal velocity of the solid particles, the particles will be carried out of the bed by the air.

On the other hand, when the air flow rate is decreased, the pressure drop remain constant and the bed height decreased as shown in figure 2.6-1. However, the final bed height may be higher than the initial height before fluidization, because the bed has higher void after it is fluidized.

Study of fluidization phenomena in laboratory of department of Chemical Engineering, Faculty of Engineer, Chulalongkorn University is carried out using the "Fluidisation and Fluid Bed Heat Transfer Unit H692" as shown in figure 2.6-2.

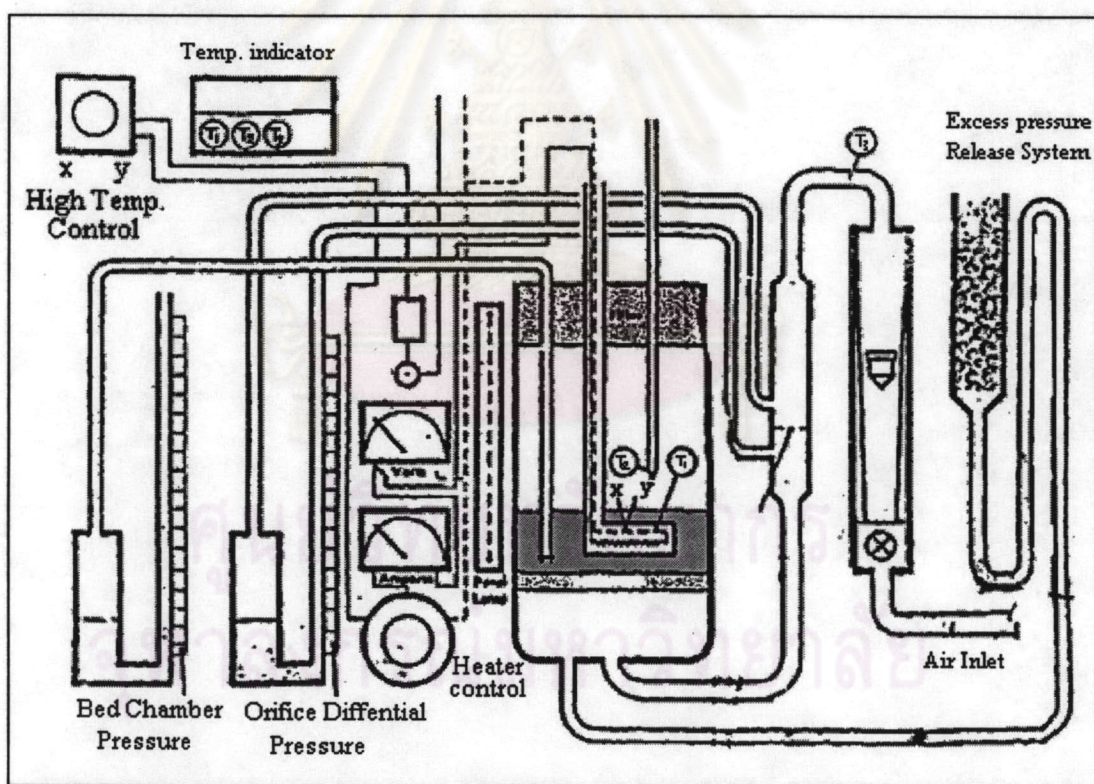


Figure 2.6-2 Fluidisation and Fluid Bed Heat Transfer Unit H692.

Data collected from this apparatus can be used for calculating superficial velocity and surface heat transfer coefficient as follows:

1) Volume flow rate through bed, V_b (m^3/sec)

$$V_b = V_m \frac{T_2}{T_3} \quad (2.6-1)$$

where V_m = air flow rate (m^3/sec).
 T_2 = bed temperature (K).
 T_3 = air temperature (K).

2) Superficial velocity, u (m/sec)

$$u = \frac{V_b}{S_b} \quad (2.6-2)$$

where S_b = cross sectional area of the chamber (m^2).

3) Heat transfer rate, Q (Watt)

$$Q = E \times I \quad (2.6-3)$$

where E = heater voltage (Volt).
 I = heater current (Ampere).

4) Surface heat transfer coefficient, h ($\text{W}/\text{m}^2\text{-K}$)

$$h = \frac{Q}{A(T_1 - T_2)} \quad (2.6-4)$$

where A = surface area of heater (m^2).
 T_1 = heater surface temperature (K).

2.7 Mixing

Mixing is an important part of all chemical processing. Both mass and heat transfer are greatly influenced by this unit. The equipment using in liquid mixing is composed of a cylindrical vessel which can be closed or opened to the air and an

impeller mounted on a shaft driven by an electric motor. A typical liquid mixing system is shown in figure 2.7-1.

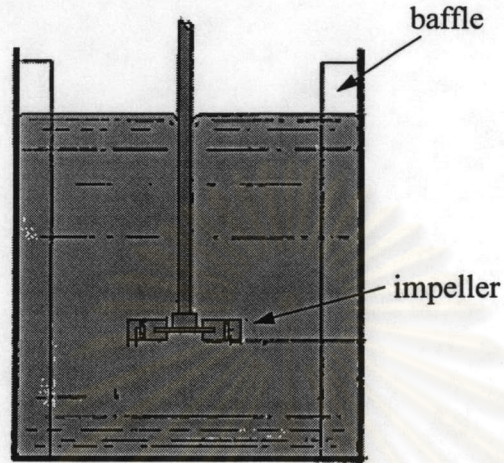


Figure 2.7-1 Liquid mixing system.

In design of a liquid mixing system, the following dimensionless groups are taken into consideration:

$$\text{Power number} \quad N_p = \frac{Pg_c}{\rho N^3 D_a^5} \quad (2.7-1)$$

$$\text{Reynolds number} \quad N_{Re} = \frac{\rho N D_a^2}{\mu} \quad (2.7-2)$$

$$\text{Froude number} \quad N_{Fr} = \frac{N^2 D_a}{g} \quad (2.7-3)$$

where

ρ = liquid density

μ = liquid viscosity

N = revolutions per unit time

D_a = diameter of agitator

P = power requirement in mixing.

Ruston, Costich and Everett (1950) used dimensional analysis to determine the power drawn by an agitator in a liquid mixing system.

$$N_p = C'(N_{Re})^x (N_{Fr})^y \left(\frac{D_T}{D_a}\right)^a \left(\frac{H_l}{D_a}\right)^b \left(\frac{H_a}{D_a}\right)^c \left(\frac{P_a}{D_a}\right)^d \left(\frac{q}{D_a}\right)^e \left(\frac{r}{D_a}\right)^f \left(\frac{W_a}{D_a}\right)^h \left(\frac{B}{N_B}\right)^g \left(\frac{R}{N_R}\right)^h$$

(2.7-4)

where

B = number of baffles

C' = dimensionless constant

D_a = agitator diameter

D_T = tank diameter

H_a = agitator height

H_l = liquid height

N_B = reference number for baffles

N_R = reference number for agitator

P_a = agitator blade pitch

q = agitator blade width

R = number of blades on the agitator

r = agitator blade length

The last nine terms in equation (2.7-4) are shape factors which define particular configuration of mixing tank. If these shape factors remain fixed, then

$$N_p = C(N_{Re})^x (N_{Fr})^y \quad (2.7-5)$$

where C is an over-all shape factor which represents the geometry of the system.

The power function, Φ is defined as

$$\Phi = \frac{N_p}{(N_{Fr})^y} \quad (2.7-6)$$

Parameter "y" is found experimentally and varies with the system configuration. Data of the power function and Reynolds number is generally plotted

on a log-log scale. This plot is called “power curve”. An individual power curve is valid for a particular geometrical configuration, but it is independent of vessel size. An example of a power curve for standard configuration tank is shown in figure 2.7-2.

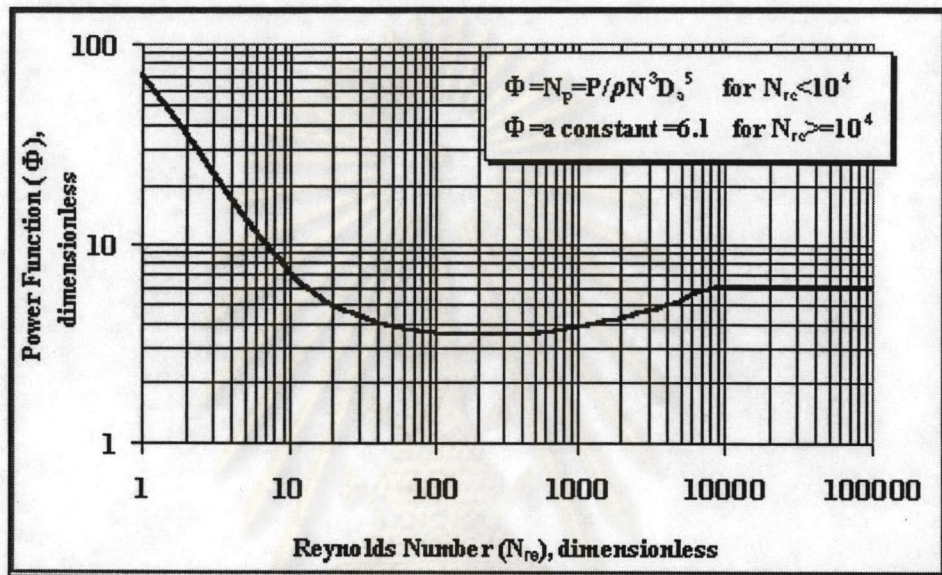


Figure 2.7-2 Power curve for standard tank configuration.

Besides studying power required by the system, this experimental unit is used to study the resident time distribution of Sodium hydroxide (NaOH) that is dissolved in water. Sodium hydroxide solution was sampled and titrated with a standard solution of Hydrochloric acid to determine its concentration. Then plot the Sodium hydroxide solution concentration profile.