MODULE 3: SOLID LIQUID SEPARATION

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SYLLABUS

- **Solid-liquid separation: Gravity settling process-** Clarifiers &Thickeners, Flocculation Design of gravity thickener. **Centrifugal settling**: principle, centrifuges for solid liquid and liquid-liquid separation.

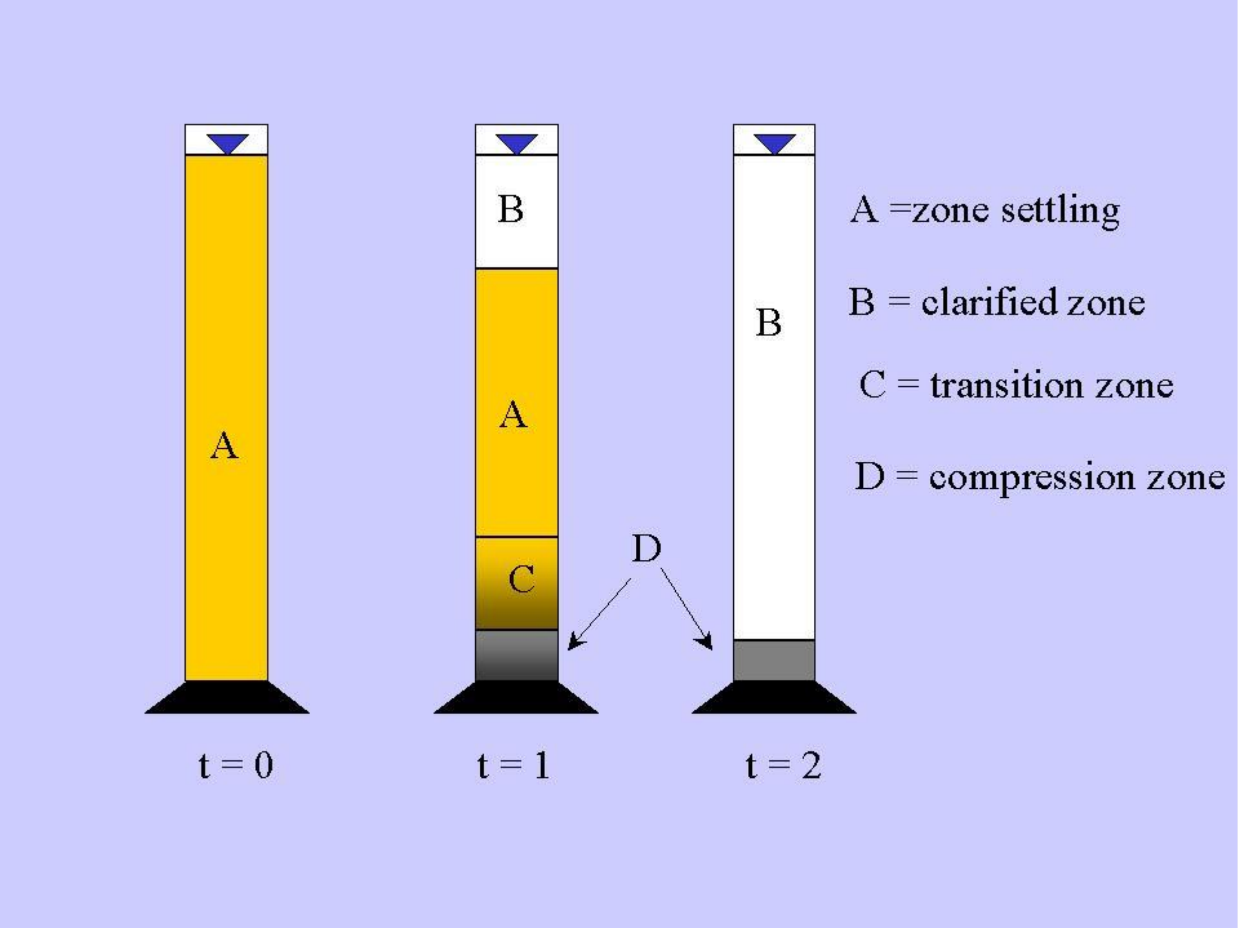
INTRODUCTION TO SOLID-LIQUID SEPARATION

- In this module the solid-liquid separation is based on movement of solid particles or liquid drops through fluid. In this study the fluid is liquid.
- The solid particles present will be eliminated from the liquid stream.
- In the separation the desired product may be solid or liquid.
- Gravity settling is the process where solid-liquid separation occurs due the movement of solid particles within liquid.

GRAVITY SETTLING PROCESSES

- In this process heavier than suspending fluid may be removed from the liquid or gas in a large settling tank.
- The fluid is velocity is very low in gravity settling tank and solids get sufficient time to settle out.
- The separation may be partial or very nearly complete.
- A settler is called clarifier where solid particles are totally removed from the liquids.
- On the other hand, classifier divides the solids in two fractions.
- The principle of operation is same for both the cases.

GRAVITY SETTLING PROCESS



MECHANISM OF SETTLING

- Particle motion through fluid
- Force balance:
- $m\frac{du}{dt} = F_e - F_b - F_D$
- $F_e = external\ force = m.a_e$
- F_b= bouncy force = $\frac{m.\rho a_e}{\rho_p}$
- F_D= drag force = $\frac{C_D u_0^2 \rho A_p}{2}$
- $m\frac{du}{dt} = m.a_e - \frac{m.\rho a_e}{\rho_p} - \frac{C_D u_0^2 \rho A_p}{2}$
- $a_e = g\ \ for\ gravity$
- $a_e = r\omega^2\ \ for\ angular\ velocity$

TERMINAL VELOCITY

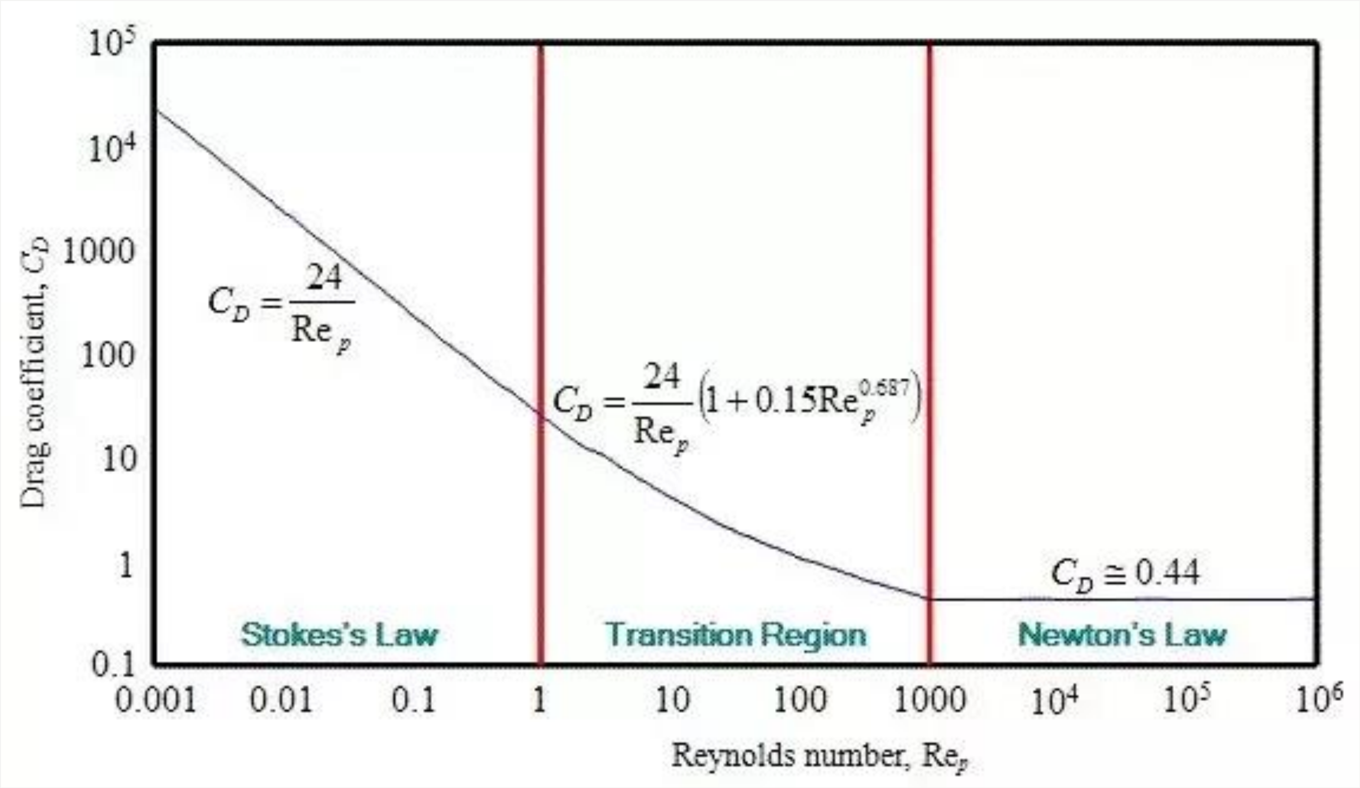
- in gravity setting the drag always increases with velocity and the acceleration decreases with time and approaches zero.
- The maximum attainable velocity by solid particle during gravity settling or free settling is called terminal settling velocity.
- $\therefore m\frac{du}{dt} = m.g - \frac{m.\rho a_e}{\rho_p} - \frac{C_D u_0^2 \rho A_p}{2} = 0$
- $u_t = \sqrt{\frac{2g(\rho_p - \rho)m}{A_p.\rho_p.\rho.C_D}}$
- For low Reynolds number spherical particle $C_D = \frac{24}{Re_p}$

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

TERMINAL VELOCITY

- $u_t = \frac{g.D_p^2(\rho_p - \rho)}{18\mu}$
- For equal terminal velocity: $\frac{D_{p1}}{D_{p2}} = \sqrt{\frac{(\rho_{p2} - \rho)}{(\rho_{p1} - \rho)}}$
- For equal density: $\frac{u_{t1}}{u_{t2}} = \frac{D_{p1}^2}{D_{p2}^2}$
- For equal size: $\frac{u_{t1}}{u_{t2}} = \frac{(\rho_{p1} - \rho)}{(\rho_{p2} - \rho)}$
- In Newton's regime $C_D = 0.44$
- $u_t = \sqrt{\frac{2g(\rho_p - \rho)m}{A_p.\rho_p.\rho.(0.44)}}$

DRAG COEFFICIENT VS REYNOLDS NO FOR SPHERICAL PARTICLE



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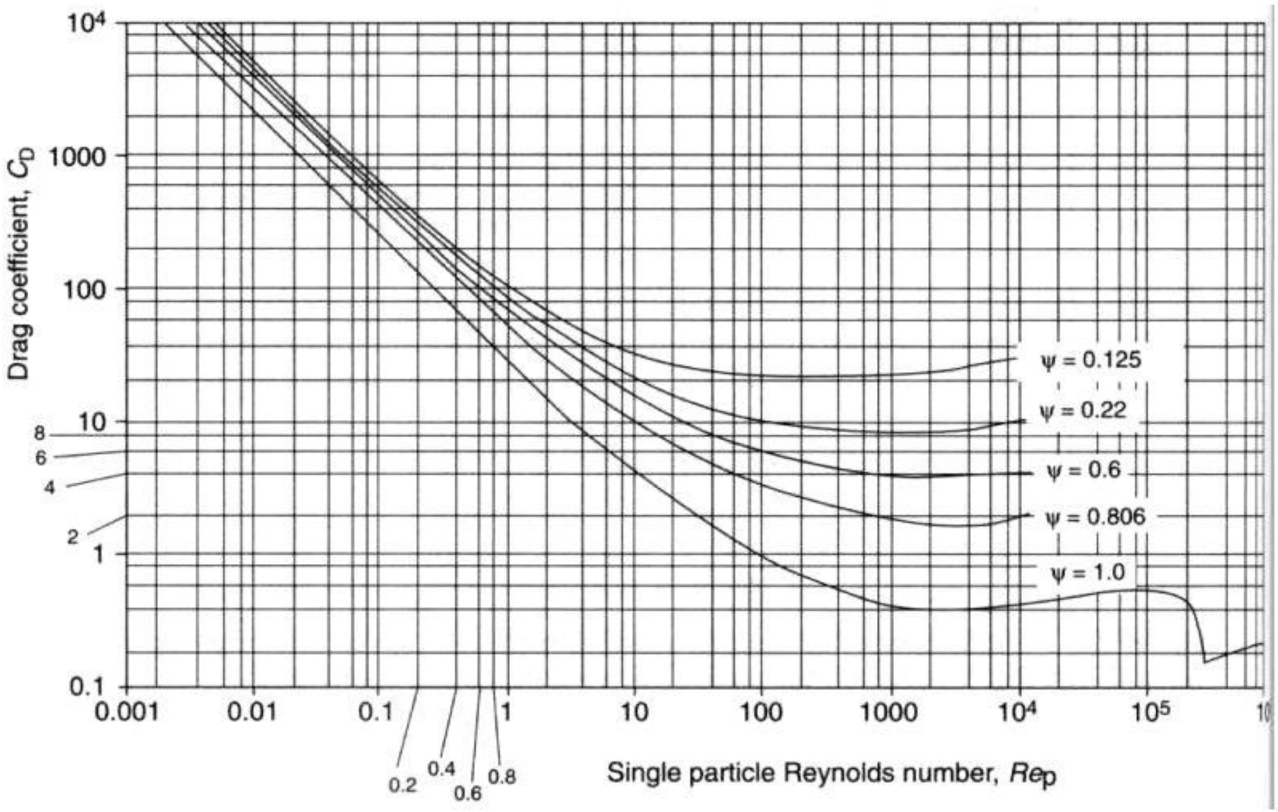
Non-spherical particles



Drag coefficient C_D versus Reynolds number Re_P for particles of sphericity ranging from 0.125 to 1.0

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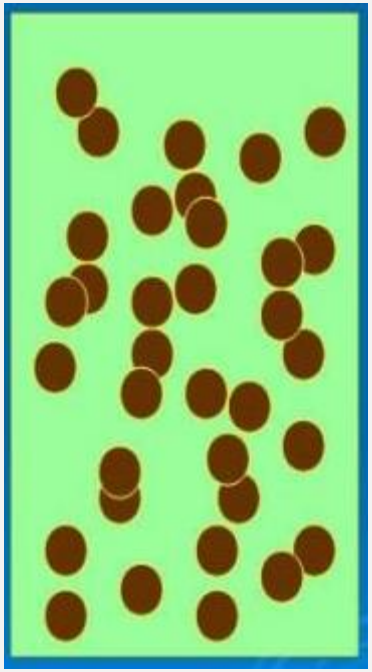
HINDERED SETTLING

- In terminal settling velocity, the velocity of a particle is not affected by the presence of other particles present in the solid-liquid mixture.
- In case of hindered settling velocity of particles affect the motion of each other.
- Usually suspension of higher concentration solution follows hindered settling.



HINDERED SETTLING

- Therefore, the equation for hindered settling velocity can be represented as:
- $u_H = \frac{g.D_p^2(\rho_p - \rho_{bf})}{18\mu_{bf}}$ (Stokes law)
- *Where,*
- $\rho_{bf} = (1-\varepsilon)\rho_p + \varepsilon\rho$ = bulk density
- $\mu_{bf} = \frac{10^{1.82(1-\varepsilon)}}{\varepsilon}\mu$ = bulk viscosity
- Relation between terminal & hindered settling velocity:
- $u_H = \frac{g.D_p^2(\rho_p - \rho_{bf})}{18\mu_{bf}}$
- $u_H = \frac{g.D_p^2(\rho_p - (1-\varepsilon)\rho_p - \varepsilon\rho)}{18\frac{10^{1.82(1-\varepsilon)}}{\varepsilon}\mu}$ (expression for bulk density & bulk viscosity are substituted)
- $u_H = \frac{g.D_p^2(\rho_p - \rho)}{18\mu}\frac{\varepsilon^2}{10^{1.82(1-\varepsilon)}}$
- $u_H = u_t \times settling\ factor$

CLASSIFIER

- In solid-liquid separation processes are closed –circuit grinding. The separations occur step by step.
- At very first step comparatively coarse particles are removed. These coarser particles are called sands. And the slurry of fine particles is call slime.

SORTING CLASSIFIER

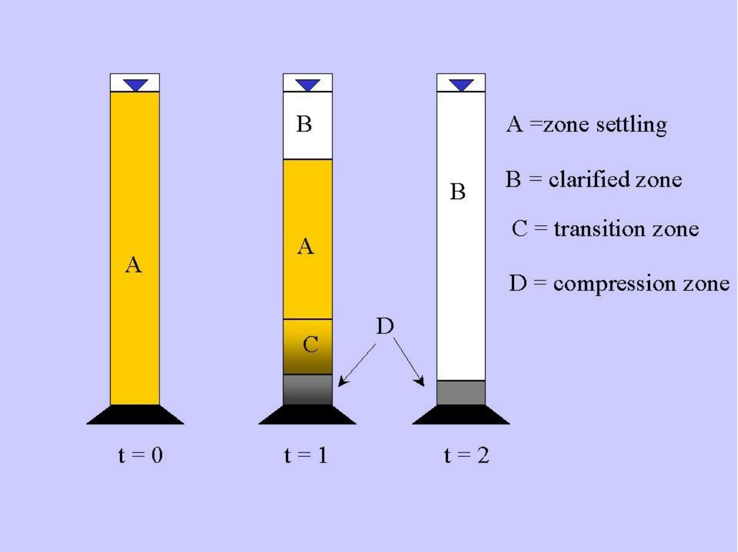
- In this device sorting occurs based on density difference.
- Sink-and-float & differential settling are two different mechanism of sorting classifier.
- In sink-and-float method the density of liquid is so chosen that heavy material particle will sink & light material particle will float. In this case separation is independent of size. The process is also known as heavy-fluid separation.
- Differential settling method utilize the difference in terminal velocities of different density materials.
- In this process the mixture of different fractions are obtained.

CLARIFIER & THICKENER

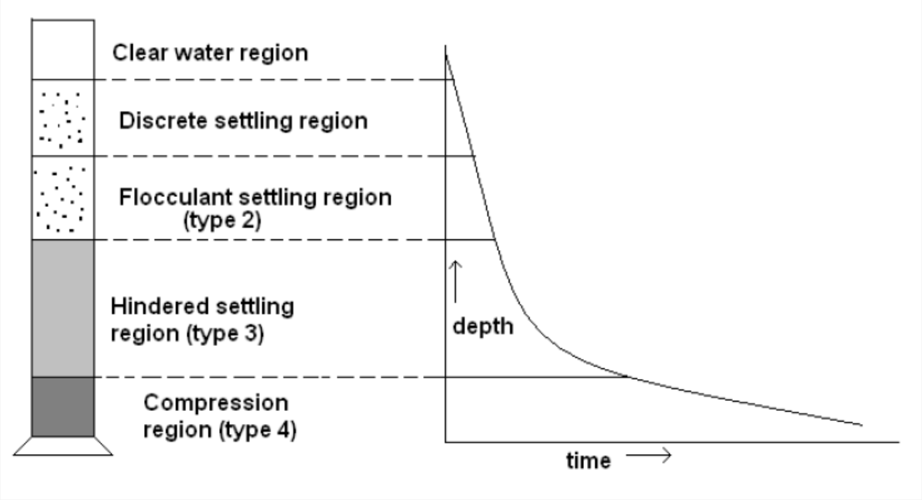
- In this separation hindered settling condition is used to convert a dilute slurry of fine particles into clarified liquid & concentrated suspension.
- Since the hindered settling velocity is lower than terminal settling velocity flocculants are added. This helps in agglomeration of fine particle which consequently improves the settling rate.
- The shape, size and density of agglomerates are not predictable and determination of settling rate is very difficult.

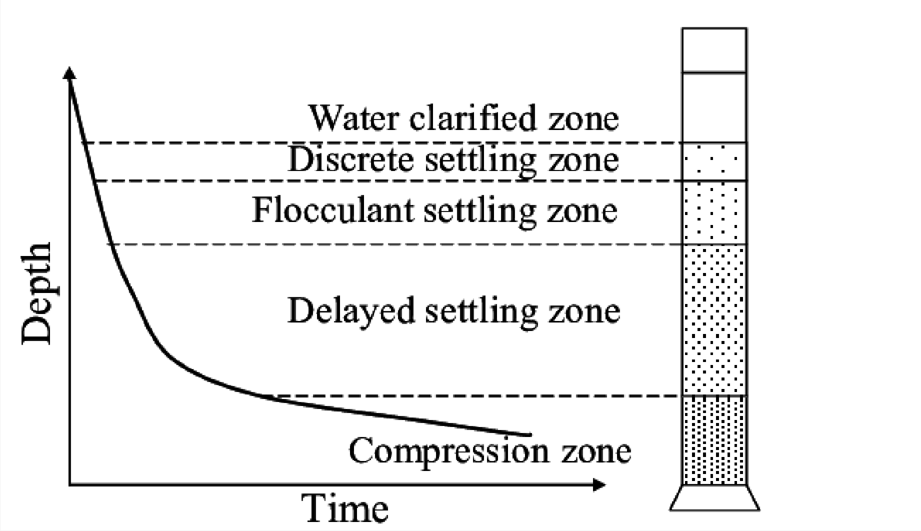
BATCH SEDIMENTATION

- At time zero only zone A with uniformly distributed solid in liquid exists.
- At time t1, a clear liquid zone B is visible and at bottom in zone D solids will start settling. A is the zone where concentration of solids remain constant since, the settling rate is constant. In zone C the rate settling will be higher.
- The level of zone A starts decreasing in next stage and settling will be constant in Zone C.
- At time t2, a clear liquid zone B & concentrated solid zone D will be obtained.
- The interface between A &C is not distinguishable. But interface between A&B and C & D are very clear.



BATCH SEDIMENTATION

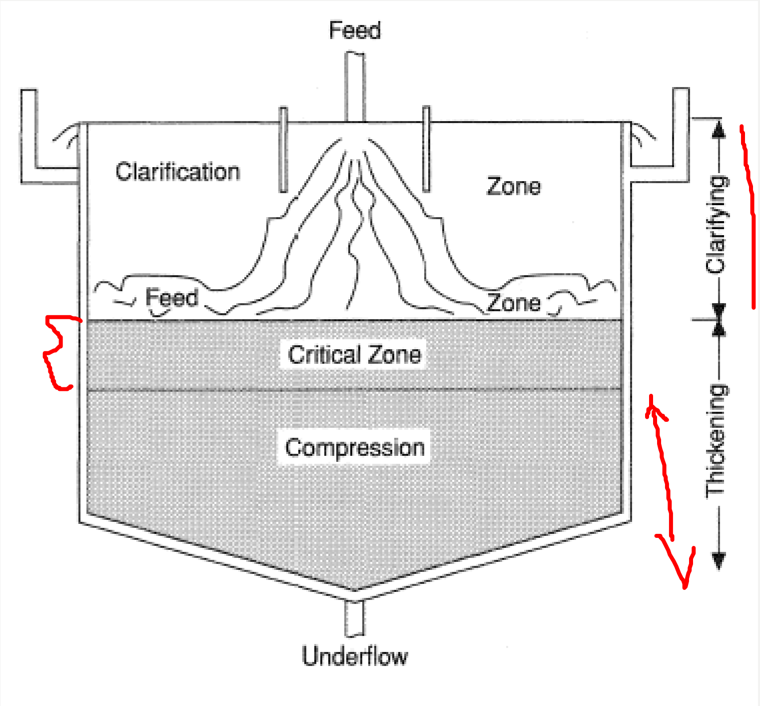




Rate of sedimentation= $\frac{dh}{dt}$

THICKENER

- Thickeners are used industrially for large scale sedimentation.
- In thickeners the sedimentation process is fast and continuous.



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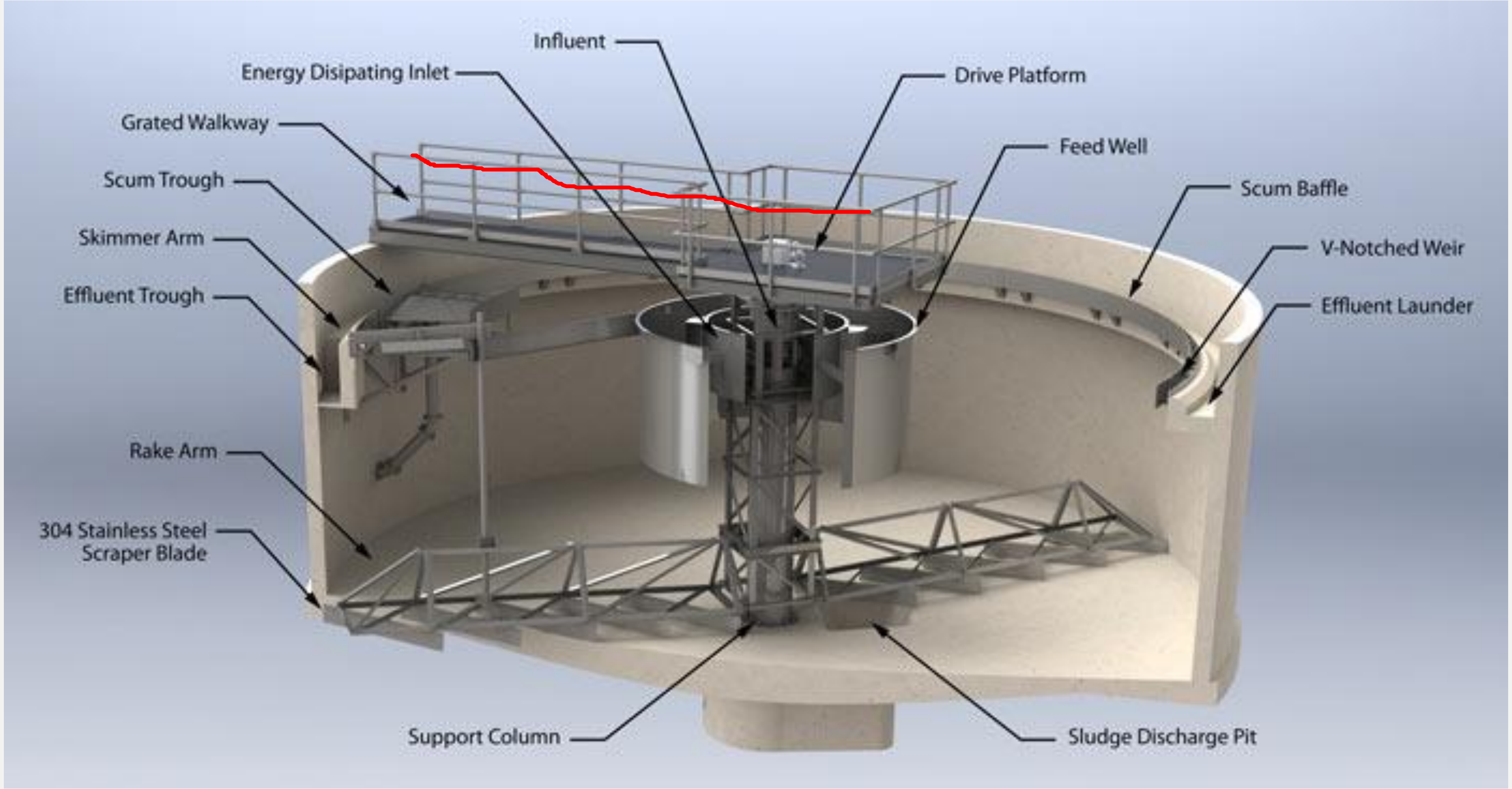
THICKENER



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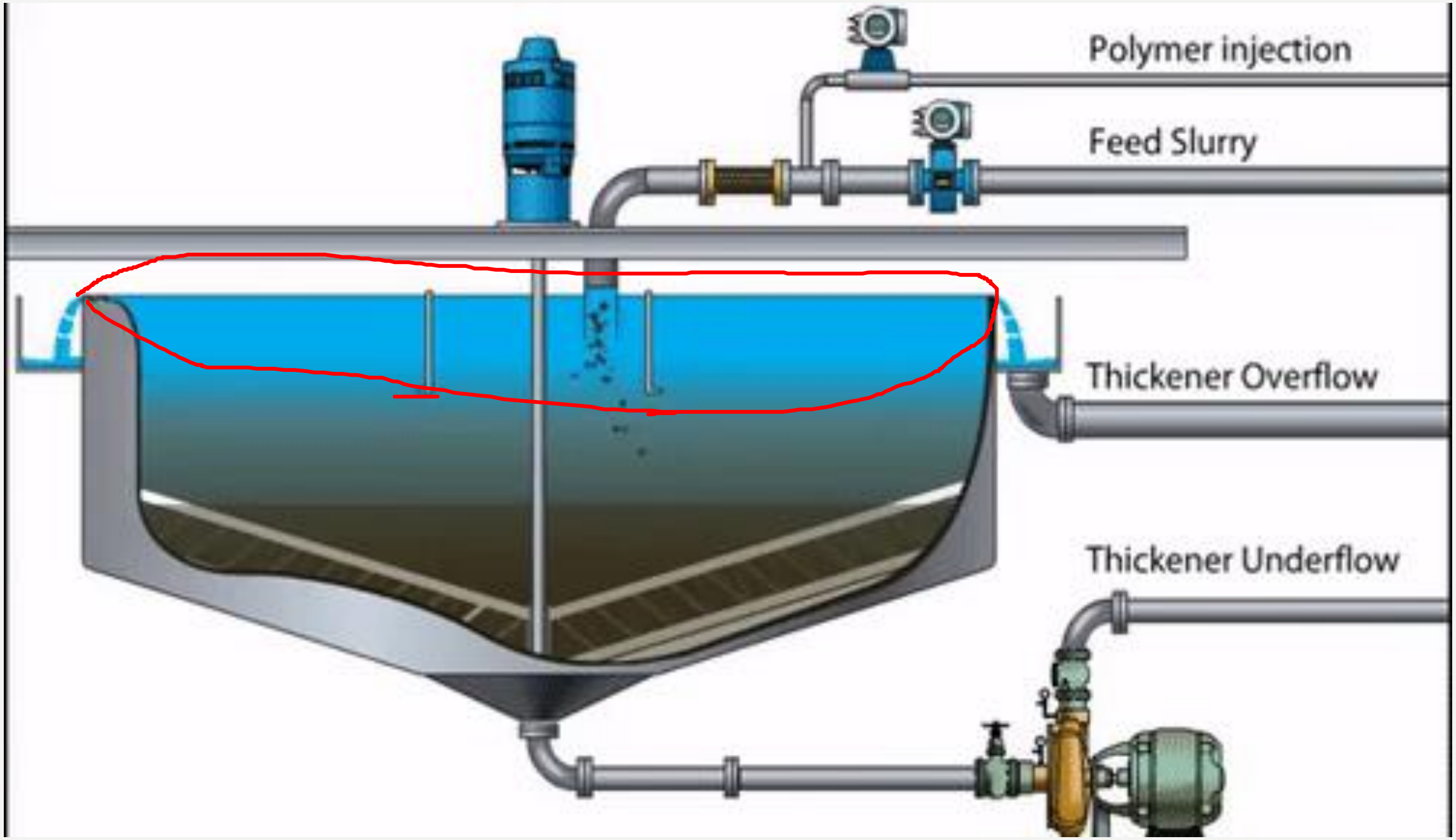
WORKING OF THICKENER



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THICKENER

- Thickener is a large, shallow tank with slow-moving radial rakes driven from a central shaft. The bottom may be flat or shallow cone.
- The feed slurry is fed from an inclined trough into the thickener. Since the density of feed slurry is higher than water the feed will flow downward until it reaches the equal density zone.
- Below equal density zone the slurry moves radially outward at decreasing velocity. This decrease in velocity results in settling of solid at bottom. And the clear liquid spills over the edge of the tank into a launder.
- The sludge are moved to the bottom with the help of agitation by rake arms.
- Diameter of mechanically agitated thickeners are 10 to 100m in diameter & 2.5 to 3.5m deep.
- Thickeners are used in waste-water treatment, cement or magnesium production from sea water.

DESIGN OF CLARIFIER & THICKENER

- The volume of clear liquor produced from a thickener depends on the cross-sectional area of the settling tank. It is almost independent of height of the tank.
- Therefore, the diameter and depth of thickener are the principle parameters of designing.
- The batch sedimentation data is used for designing of continuous thickener.

DESIGN STEPS

- The design is based on one dimensional analysis.
- The flow in clarifier is upward and in settling zone flow is downward.
- In continuous thickener the depth of layers are constant, at least for short time.
- In batch sedimentation no solid or liquid is coming out from the cylinder. Therefore, measured settling rates are valid for no net flow.
- Let us consider the solid flux in downward direction is G and It is defined as follows:
- $G = G_t + G_s$
- G_t is amount of solid in downward flow
- G_s is amount of solid in settling zone.
- $G = G_t + G_s = uc + \left(\frac{dz}{dt}\right) c$

DESIGN STEPS

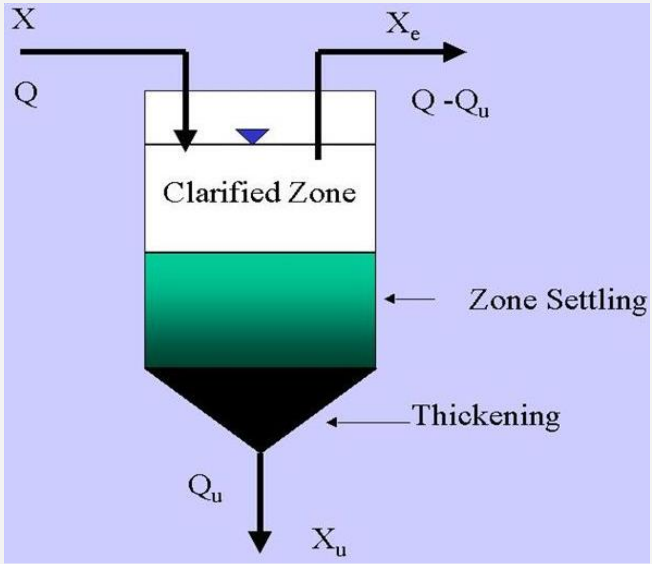
Stream	Flow-rate (m^3/s)	Concentration (kg/m^3)
Inlet	Q	X
Over-flow	$Q - Q_u = Q_0$	$X_e = 0$
Under-flow	Q_u	X_u

- Material balance

Solid balance: $Q \times X = Q_u \times X_u$

Fluid balance:

$$Q\left(1 - \frac{X}{\rho}\right) - Q_u\left(1 - \frac{X_u}{\rho}\right) = Q_0$$



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DESIGN STEPS

Fluid balance:

$$Q\left(1-\frac{X}{\rho}\right)-Q_u\left(1-\frac{X_u}{\rho}\right)=Q_0$$

- By substituting $Q_u=\frac{Q\times X}{X_u}$
- $Q\left(1-\frac{X}{\rho}\right)-\frac{Q.X}{X_u}\left(1-\frac{X_u}{\rho}\right)=Q_0$

Or $Q.X\left[\frac{1}{X}-\frac{1}{X_u}\right]=Q_0$

Or mass flow inlet $=M=\frac{Q_0}{\left[\frac{1}{X}-\frac{1}{X_u}\right]}$

Or $\text{Flux}=\frac{M}{A_r}=\frac{\frac{Q_0}{A_r}}{\left[\frac{1}{X}-\frac{1}{X_u}\right]}=\frac{Settling\ velocity}{\left[\frac{1}{X}-\frac{1}{X_u}\right]}$

DESIGN STEPS

- Capacity limiting layer:
- The concentration inside the sedimentation tank and in underflow are not same. Therefore, a layer must be considered where the concentration is almost constant. This layer is known as Capacity limiting layer.
- Let us assume the L, X_L are the flowrate and concentration at the inlet to Capacity limiting layer.
- The final design equation is

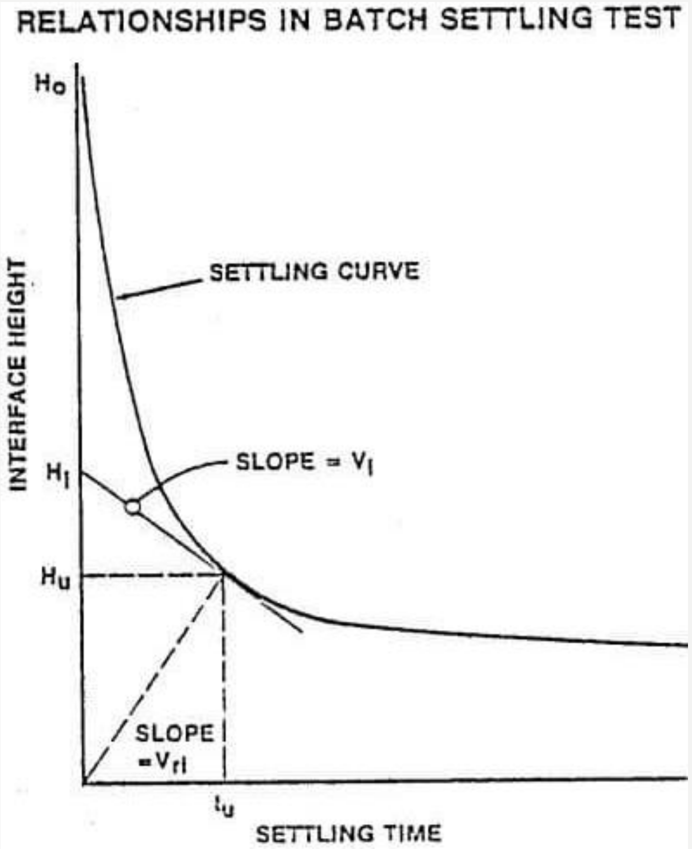
$$\frac{L.X_L}{A_r} = \frac{Settling\ velocity}{\left[\frac{1}{X_L} - \frac{1}{X_u}\right]}$$

DESIGN STEPS

- $\frac{L.X_L}{A_r} = \frac{\text{Settling velocity}}{\left[\frac{1}{X_L} - \frac{1}{X_u}\right]}$
- Settling velocity will be calculated from the batch sedimentation curve. Slop of the tangent to the curve will give the settling velocity at corresponding time.
- Calculation of X_L:

$$H_I.X_L = H_0.X$$

- Draw the following graphs.



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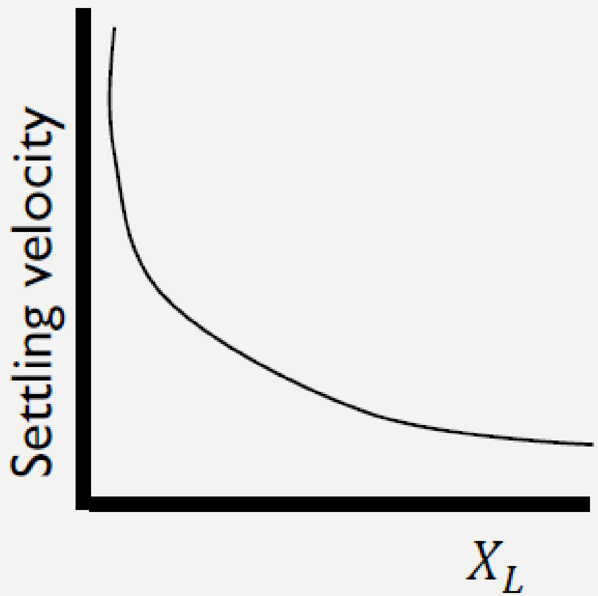
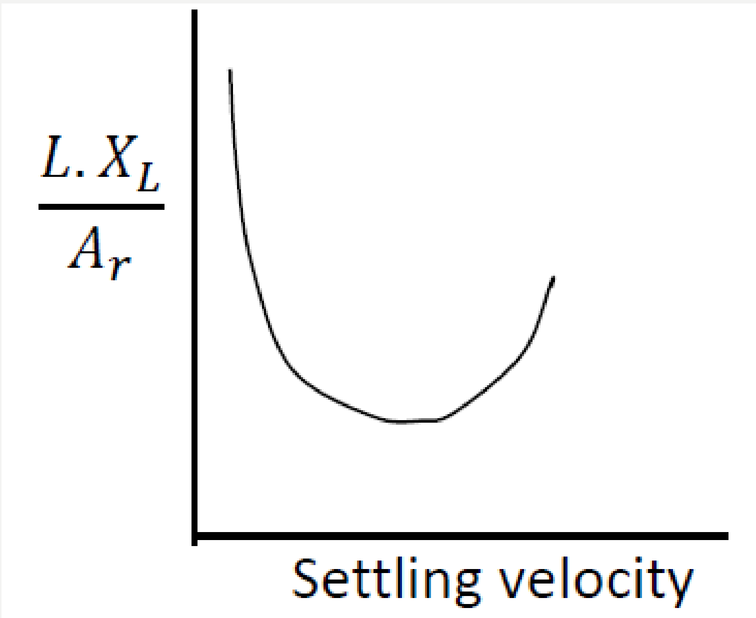
DESIGN STEPS



- Calculate Ar from minimum value of $\frac{L.X_L}{A_r}$.



DESIGN STEPS

- After calculating the area of thickener now the height of thickener will be calculated.
- The depth of compression zone within the retention time will be determined first.
- Retention time is $(t_u - t_c)$.
- t_u is the time required to reach the concentration X_u.
- t_c is the time at which all solids enter the solid zone.
- Let us assume the volume of compression zone
  $V_c = volume\ of\ solid + volume\ of\ liquid\ in\ compression\ zone$

DESIGN STEPS

- $V_c = \frac{M}{\rho}(t_u - t_c) + \mathrm{M}\int_{t_c}^{t_u}\left(\frac{1}{X_L} - \frac{1}{\rho}\right)dt$
- $V_c = \frac{M}{\rho}(t_u - t_c) + \mathrm{M}\int_{t_c}^{t_u}\frac{1}{X_L}dt - \frac{M}{\rho}\int_{t_c}^{t_u}dt$
- $V_c = \mathrm{M}\int_{t_c}^{t_u}\frac{1}{X_L}dt$
- t_u can be calculated from X_u
- But the calculation of t_c is very difficult. Robert proposed that in compression zone rate of settling varies linearly with time.

$$\frac{dH}{dt} = -k(H - H_u)$$

$$or\ \frac{H - H_u}{H_0 - H_u} = -kt$$

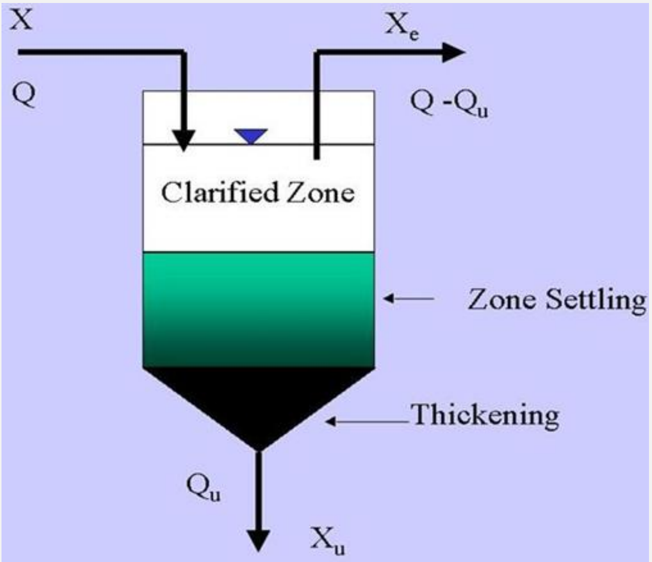
NUMERICAL

- A slurry consists of 2% by weight of solids with density 2500 kg/m3 is to be clarified by continuous sedimentation. Feed to the clarifier is 5000m3/day. The underflow contains 10% solids. Design the thickener.
- Batch sedimentation test data is

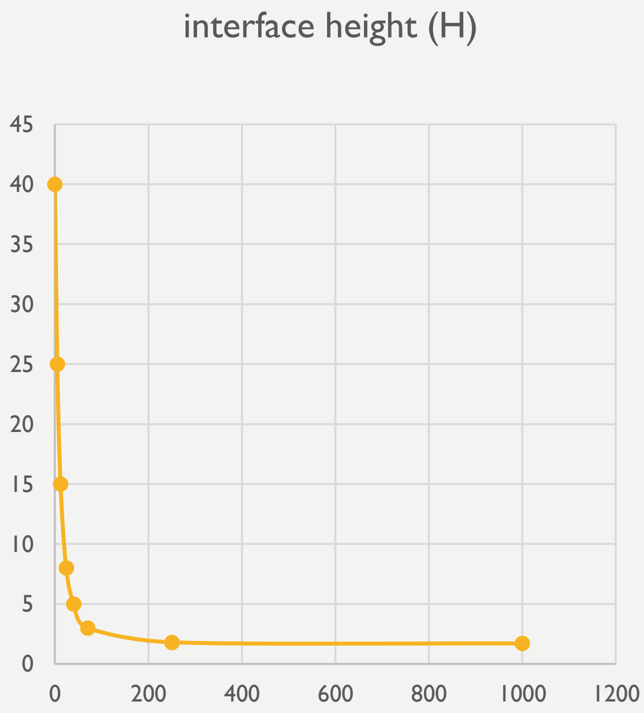
Time (min)	0	5	12	24	40	70	250	1000
Height of interface(H) (cm)	40 (H_0)	25	15	8	5	3	1.8	1.7 (H_u)

SOLUTION

- Feed concentration is 2% by weight
- $X = \frac{2}{\frac{2}{2500}+\frac{98}{1000}}$
- The underflow contains 10% solids
- $X_u = \frac{10}{\frac{10}{2500}+\frac{90}{1000}}$



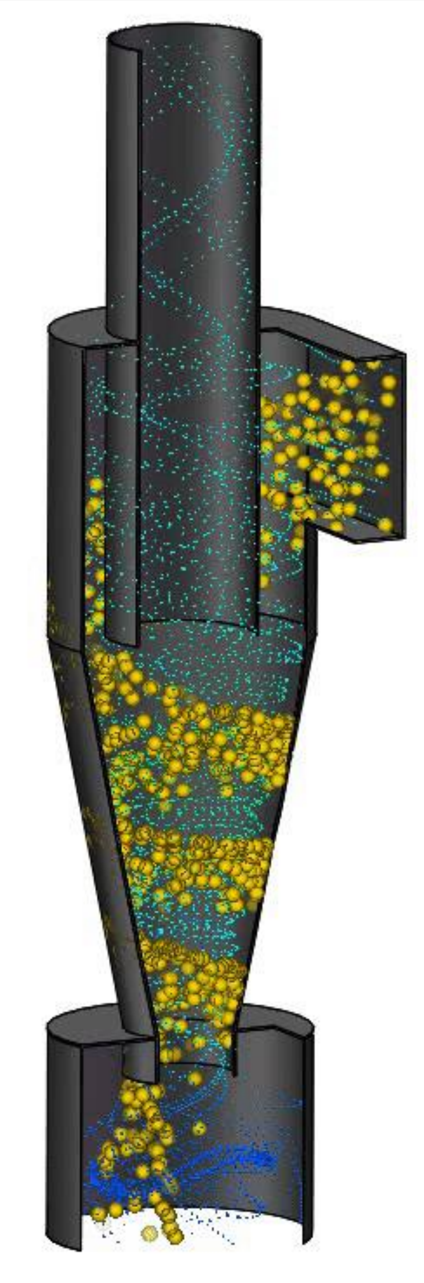
- Complete the problem as discussed in the class.



CENTRIFUGAL SETTLING

- The gravity settling process is very slow process. Therefore to increase the settling rate the force of gravity acting on the particle are replaced by stronger centrifugal force.
- The size of centrifugal separation units are small, and it can efficiently remove the fine particles.

CYCLONES



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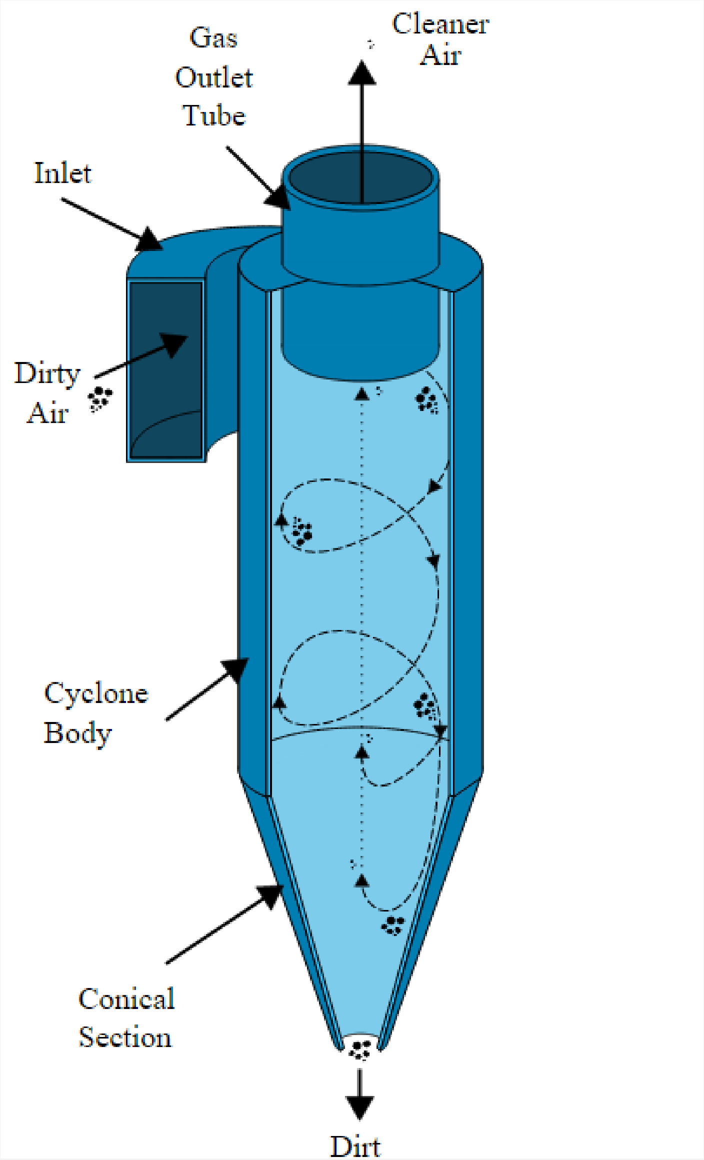
CYCLONES

- Cyclones remove solid particles from gas stream.



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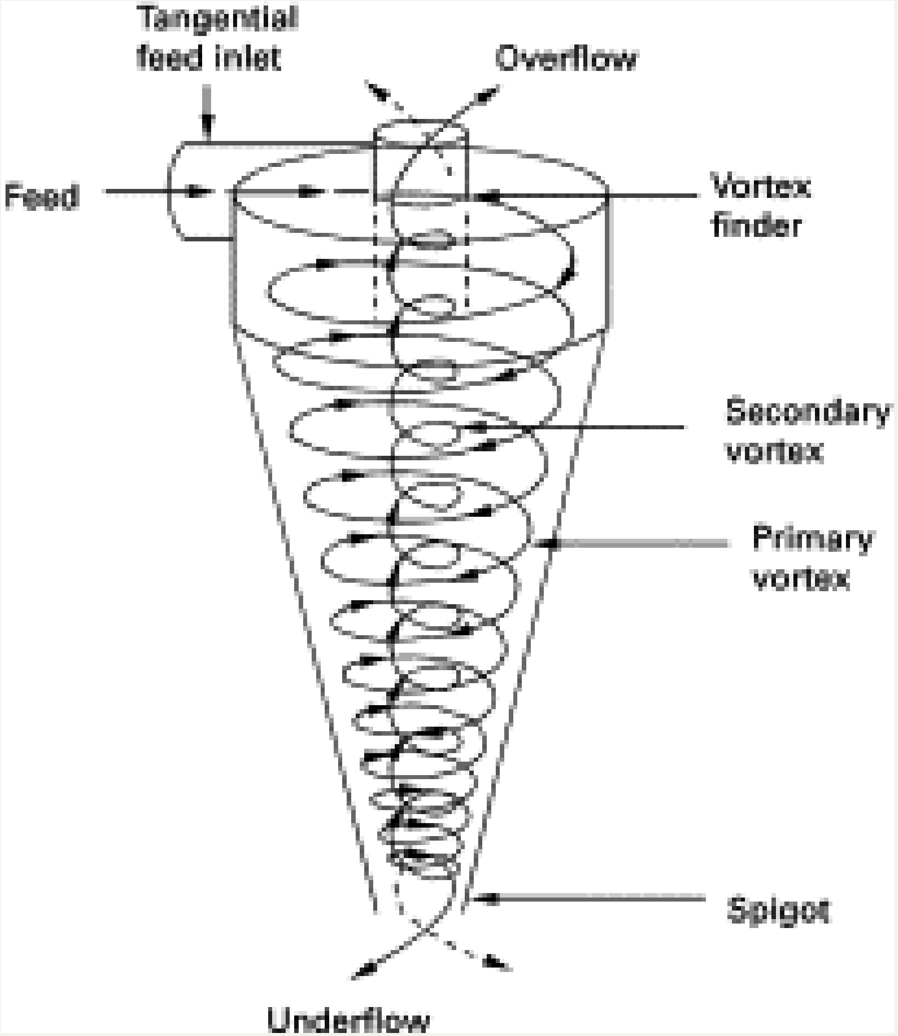
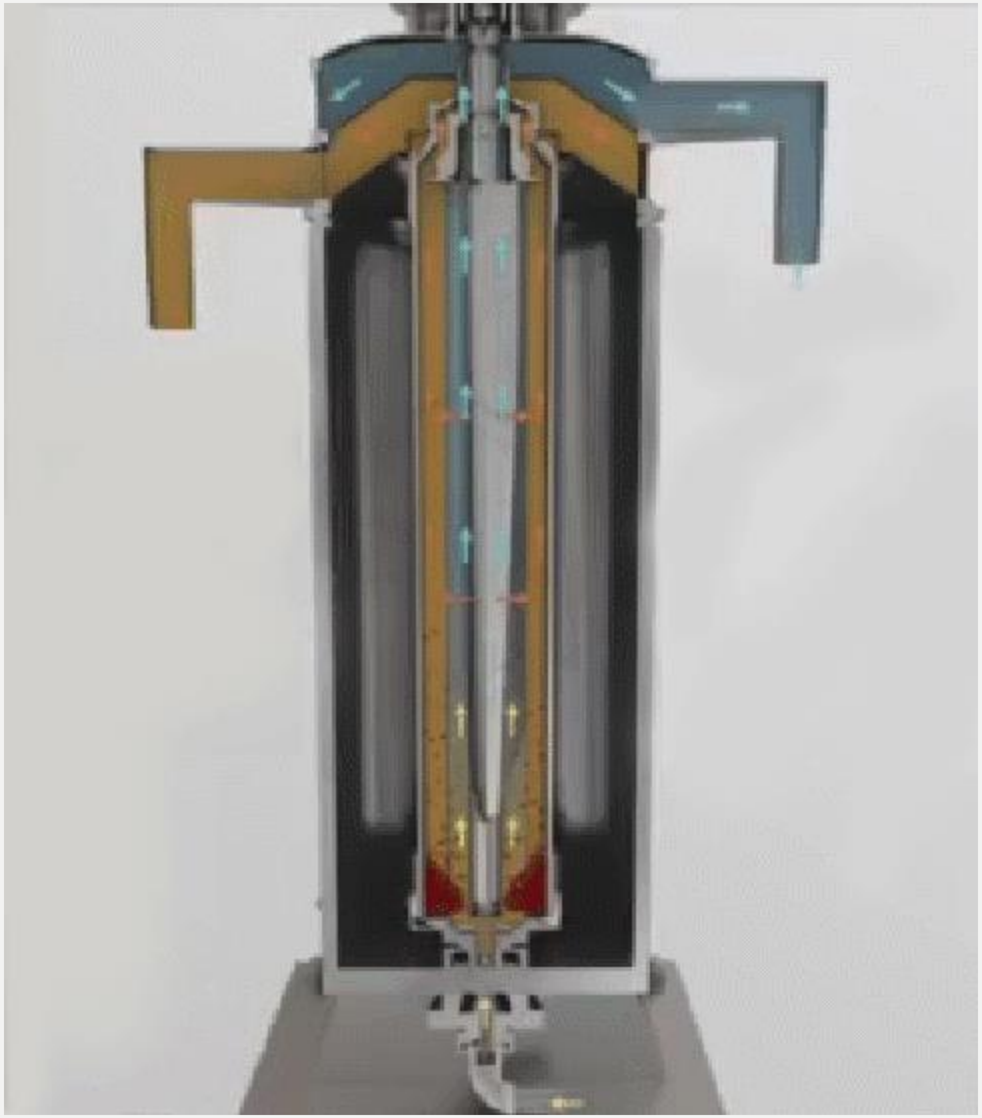
HYDRO-CYCLONES

- Hydro-cyclone separates solid particles from liquid.
- It is a thickener.

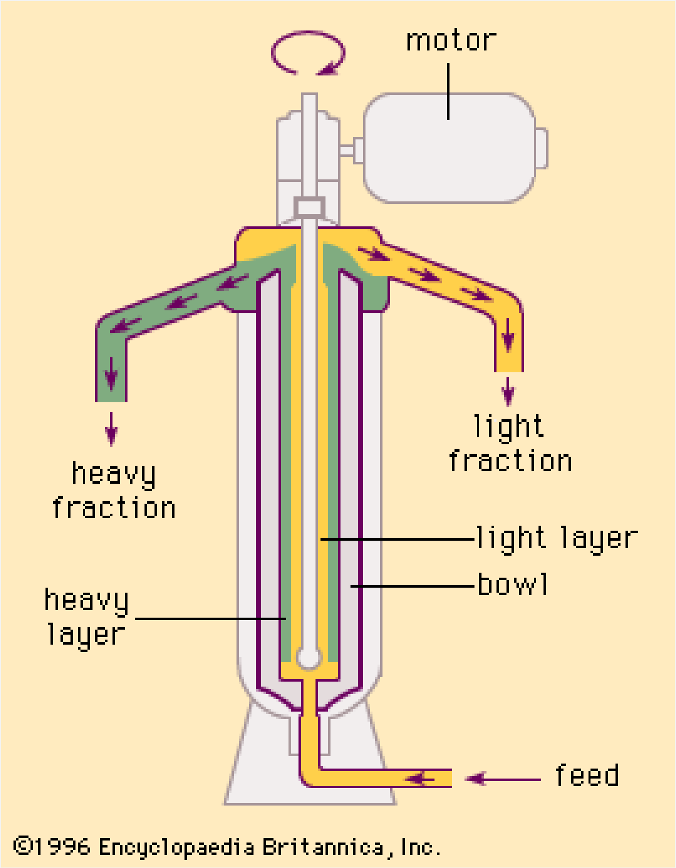


TUBULAR CENTRIFUGE

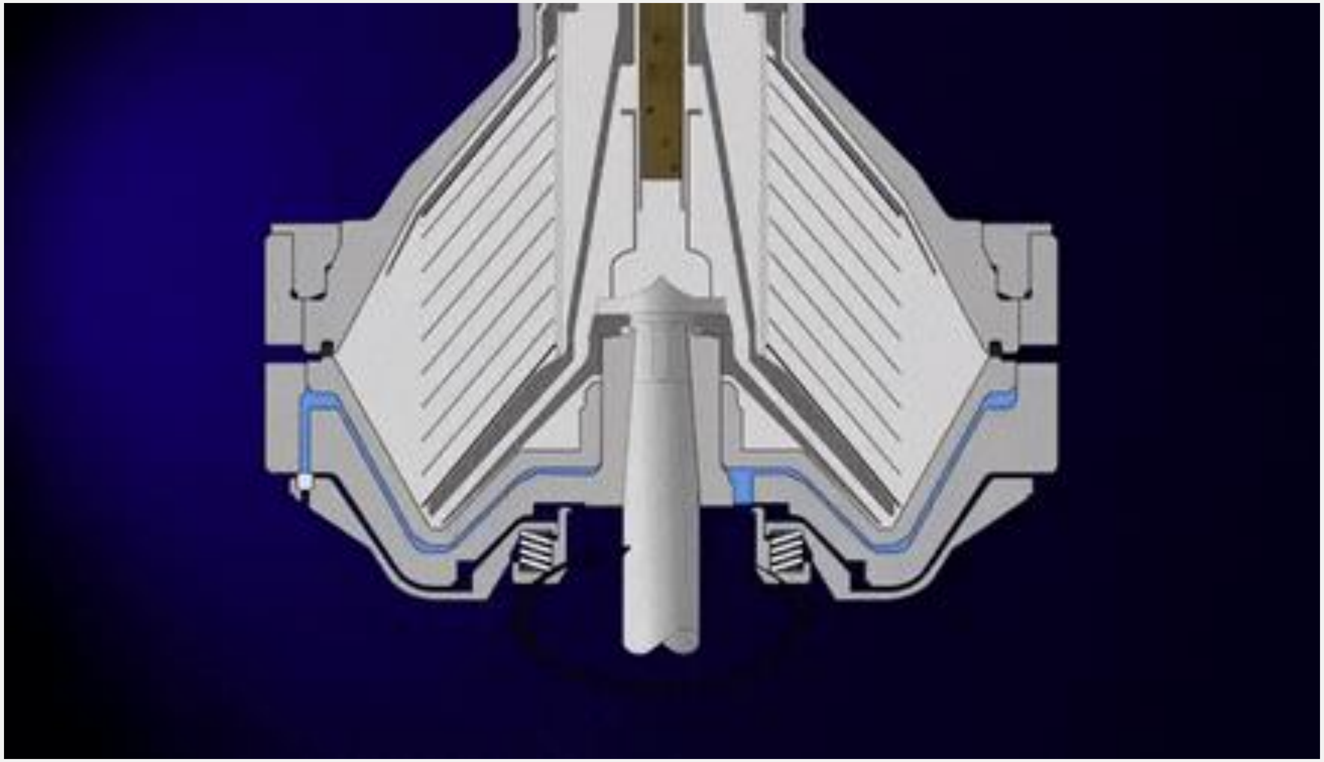


TUBULAR CENTRIFUGE

- Centrifuges are used to separate immiscible liquids.
- In tubular centrifuge bowl rotates at very high r.p.m (15000) and generates a high centrifugal force.



DISK CENTRIFUGE



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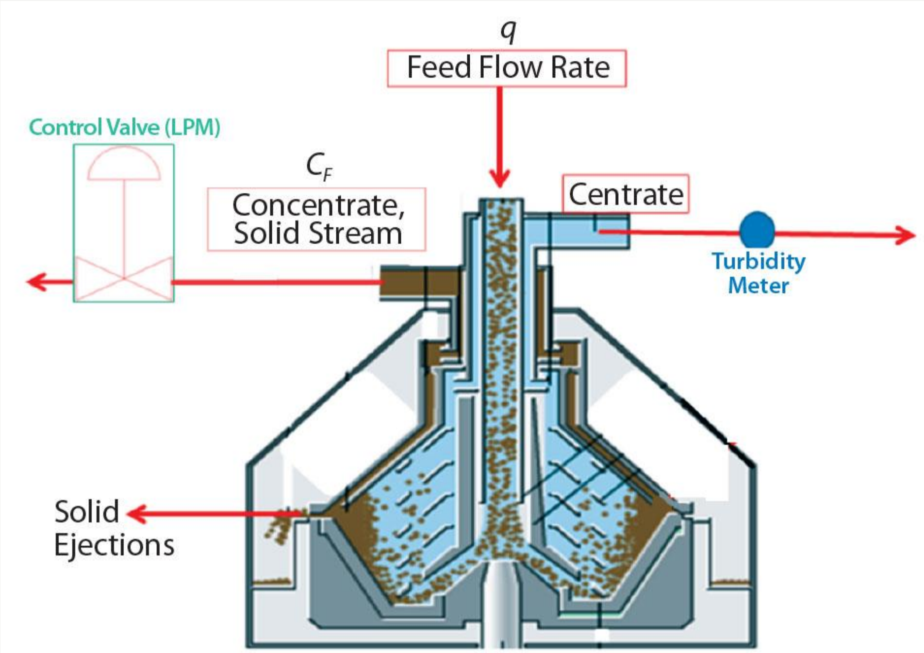
DISK CENTRIFUGE

- Disk centrifuges are used in separation of cream from milk and to increase the concentration of rubber latex.
- Complete separation is not possible.
- The considerable shearing at liquid-liquid interface helps to break the emulsions present in solution.



PRINCIPLE OF CENTRIFUGAL SEDIMENTATION

- In a sedimenting centrifuge a particle of given size is removed from the liquid if sufficient time is available for the particle to reach the wall of the centrifuge.
- The given figure describes the feeding from bottom and discharging from top.
- Liquid moves upward at a constant velocity & solids start settling at distance rA from the axis of rotation.
- It is also assumed at the end of residence time the particle will move from rA to rB.

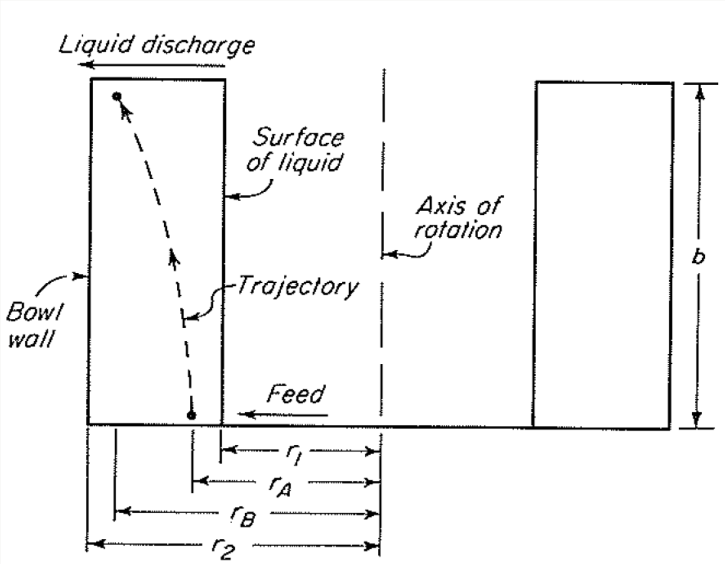


FIGURE 30.45
Particle trajectory in sedimenting centrifuge.

PRINCIPLE OF CENTRIFUGAL SEDIMENTATION

- The particles will settle with terminal settling velocity (Stokes' law)

$$u_t = \frac{\omega^2 . r . D_p^2 (\rho_p - \rho)}{18\mu}$$

$$or \ \frac{dr}{dt} = \frac{\omega^2 . r . D_p^2 (\rho_p - \rho)}{18\mu}$$

$$or \ \frac{dr}{r} = \frac{\omega^2 . D_p^2 (\rho_p - \rho)}{18\mu} dt$$

$$\therefore \int_{r_A}^{r_B} \frac{dr}{r} = \frac{\omega^2 . D_p^2 (\rho_p - \rho)}{18\mu} t_T$$

$$or \ t_T = \frac{18\mu}{\omega^2 . D_p^2 (\rho_p - \rho)} ln \frac{r_B}{r_A}$$

PRINCIPLE OF CENTRIFUGAL SEDIMENTATION

- Therefore the residence time is

$$t_T = \frac{18\mu}{\omega^2 . D_p^2 (\rho_p - \rho)} ln \frac{r_B}{r_A}$$

- The residence time is volumetric flowrate of solution by volume of liquid in centrifuge.

$$\frac{V}{q} = t_T = \frac{18\mu}{\omega^2 . D_p^2 (\rho_p - \rho)} ln \frac{r_B}{r_A}$$

$$q = \frac{\omega^2 . D_p^2 (\rho_p - \rho)}{18\mu} \frac{V}{ln \frac{r_B}{r_A}} = \frac{\omega^2 . D_p^2 (\rho_p - \rho)}{18\mu} \frac{\pi b (r_2^2 - r_1^2)}{ln \frac{r_B}{r_A}}$$

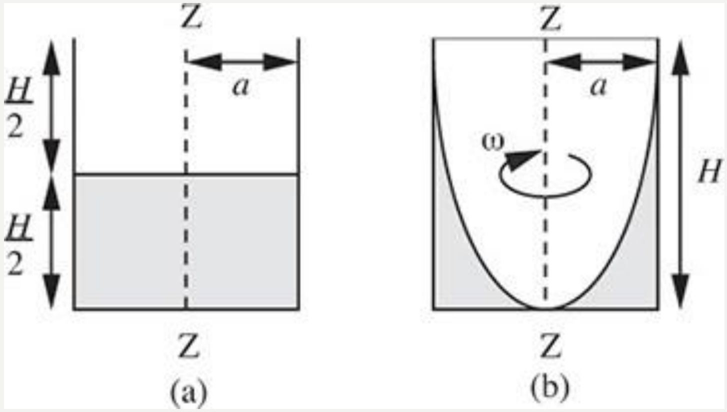
CUT DIAMETER

- Cut diameter is the diameter of that particle which reaches one-half the distance between r1 & r2.
- If Dpc is the cut diameter than rA= (r2+r1)/2
- Now if that particle is to be removed from liquid B will be equal to r2.
- Therefore the flow rate corresponds to cut diameter is

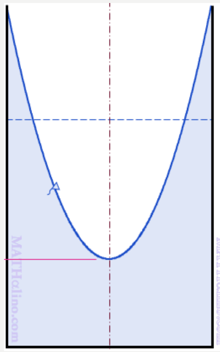
$$q_c = \frac{\omega^2 . D_{pc}^2 \left(\rho_p - \rho\right)}{18\mu} \frac{\pi b (r_2^2 - r_1^2)}{ln \frac{2r_2}{r_2 + r_1}}$$

The particle size greater than Dpc will be separated at the above flowrate (qc)

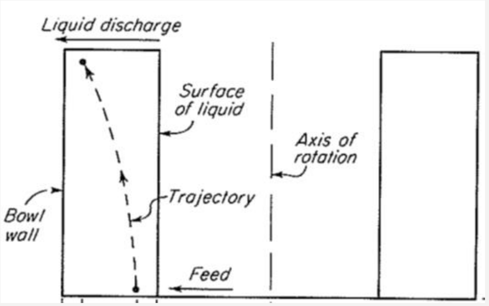
LIQUID PROFILE INSIDE CENTRIFUGE



https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.informit.com%2Farticles%2Farticle.aspx%3Fp%3D2832417%26seqNum%3D7&psig=AOvVaw0PcmUfAg0TWHB7hWwvkR5f&ust=1602738255985000&source=images&cd=vfe&ved=0CAIQjRxqFwoTCPCX3Lans-wCFQAAAAAdAAAAABAw



(c)



(d)

- With increase in rotational speed the vertex of parabola starts shifting toward bottom and at higher rotational speed the liquid profile becomes cylindrical.
- At very low rotational speed the vertex will be within the bowl (fig (c))
- At moderate speed, the profile will be like fig (b)
- At high speed, the profile will be like fig (d)
- The expression for volume of liquid inside cavity will be different for each cases.

SIGMA VALUE

- For very small thickness of liquid layer $r_2 \approx r_1$ the terminal settling velocity will be $u_t = \frac{\omega^2 . r_2 . D_p^2(\rho_p - \rho)}{18\mu}$
- Therefore, the velocity will be constant and residence time becomes

$$\int_{r_A}^{r_B} \frac{dr}{r_2} = \frac{\omega^2 . D_p^2(\rho_p - \rho)}{18\mu} t_T$$

$$or\ t_T = \frac{18\mu}{\omega^2 . D_p^2(\rho_p - \rho)} \frac{r_B - r_A}{r_2} = \frac{r_B - r_A}{u_t}$$

If the liquid thickness is s & the settling distance for cut diameter is s/2

$$u_t = \frac{s}{2t_T}$$

$$or\ q_c = \frac{V}{t_T} = \frac{2V . u_t}{s} = \frac{2V .}{s} \frac{\omega^2 . r_2 . D_p^2(\rho_p - \rho)}{18\mu}$$

SIGMA VALUE

- $q_c = \frac{2V.}{s} \frac{\omega^2.r_2.D_p^2(\rho_p - \rho)}{18\mu}$
- $q_c = \frac{2V\omega^2.r_2.}{s.g} \frac{D_p^2(\rho_p - \rho)g}{18\mu}$
- $q_c = \frac{2V\omega^2.r_2.}{s.g} u_{tg}$
- $q_c = 2 \sum u_{tg} = \sum u_{tg}$
- u_{tg} is terminal settling velocity due to gravity & sigma ($\sum$) is characteristic of the centrifuge. sigma ($\sum$) is the cross-sectional area of gravity settling tank of same separation capacity as the centrifuge.

NUMERICAL

What is the capacity in cubic meters per hour of a clarifying centrifuge operating under the following conditions?

Diameter of bowl, 600mm

Thickness of liquid layer, 75mm

Depth of bowl, 400mm

Speed 1200 r/min

Sp. Gravity of liquid 1.2

Sp. Gravity of solid 1.6

Viscosity of liquid 2 cP

Cut size of particles, 30μm

$$q_c = \frac{\omega^2 . D_{pc}^2 (\rho_p - \rho)}{18\mu} \frac{\pi b (r_2^2 - r_1^2)}{ln \frac{2r_2}{r_2 + r_1}}$$

SOLUTION

- $q_c = \frac{\omega^2 . D_{pc}^2 (\rho_p - \rho)}{18\mu} \frac{\pi b (r_2^2 - r_1^2)}{ln \frac{2r_2}{r_2 + r_1}}$

Diameter of bowl, 600mm

Thickness of liquid layer, 75mm

Depth of bowl, 400mm

Speed 1200 r/min

Sp. Gravity of liquid 1.2

Sp. Gravity of solid 1.6

Viscosity of liquid 2 cP

Cut size of particles, 30μm

$$r_2 = 0.6m$$
$$r_2 - r_1 = 0.075m$$
$$r_1 = (0.6 - 0.075)m = 0.525m$$
$$b = 0.4m$$
$$\omega = \frac{1200}{60} = 20rps$$
$$\rho_p = 1600 \text{ kg}/m^3$$
$$\rho = 1200 \text{ kg}/m^3$$
$$\mu = 2cP = 0.02\ Pa.s$$
$$D_{pc} = 30 \times 10^{-6}m$$

$$q_c = \frac{20^2 \times (30 \times 10^{-6})^2 (1600 - 1200)}{18 \times 0.02} \frac{\pi \times 0.4(0.6^2 - 0.525^2)}{ln \frac{2 \times 0.6}{0.6 + 0.525}}$$

NUMERICAL

- In a test on a centrifuge all particles of a mineral of density 2800 kg/m3 and of size 5μm, equivalent spherical diameter, were separated from suspension in water fed at a volumetric throughput rate of 0.25 m3/s. Calculate the value of the capacity factor $\sum$.
- What will be the corresponding size cut for a suspension of coal particles in oil fed at the rate of 0.04 m3/s? The density of coal is 1300 kg/m3 and the density of the oil is 850 kg/m3 and its viscosity is 0.01 Ns/m2. It may be assumed that Stokes' law is applicable.