MODULE 4: FILTRATION

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SYLLABUS

- Theory of solid-liquid filtration, principle of filtration, constant pressure and constant rate filtration, compressible and incompressible cakes, Filter aids, Equipment of liquid solid filtration, Batch and continuous pressure filters. Theory of centrifugal filtration, Equipment for centrifugal filtration.

INTRODUCTION

- Filtration is a process whare solids are removed from fluid by passing the solid-liquid mixture through a filtering medium or septum.
- After the process solids are collected on the septum and fluid are passes through the filter medium and collected at the bottom.
- The filtration process may be continuous or batch.
- Pressure filter, vacuum filter, centrifugal filter are different industrial filter.
- The fluid may be gas or liquid and a wide range of solid particles can be separated in this process.

APPLICATIONS

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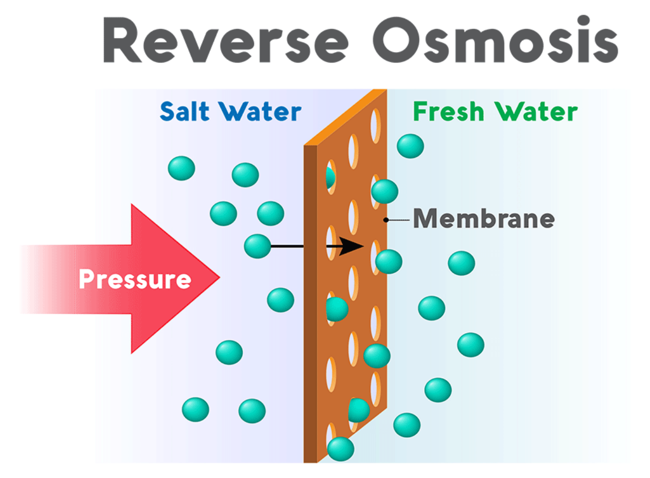

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MECHANISM OF FILTRATION

- The driving for filtration is pressure difference across the medium.
- Generally the pressure at upstream (above filter medium is at atmospheric pressure and that at the down stream (below filter medium) is vacuum.
- The pressure above atmospheric pressure can be created by using pump, blower or centrifugal force to increase the efficiency of the separation process.
- The filter medium offers the resistance to flow. Therefore as the solids deposited on the filter medium forms cake and the resistance starts increasing. The solid particles block the opening of filter medium.

TYPES OF FILTER

1. Cake filter
2. Clarifying filter
3. Crossflow filter

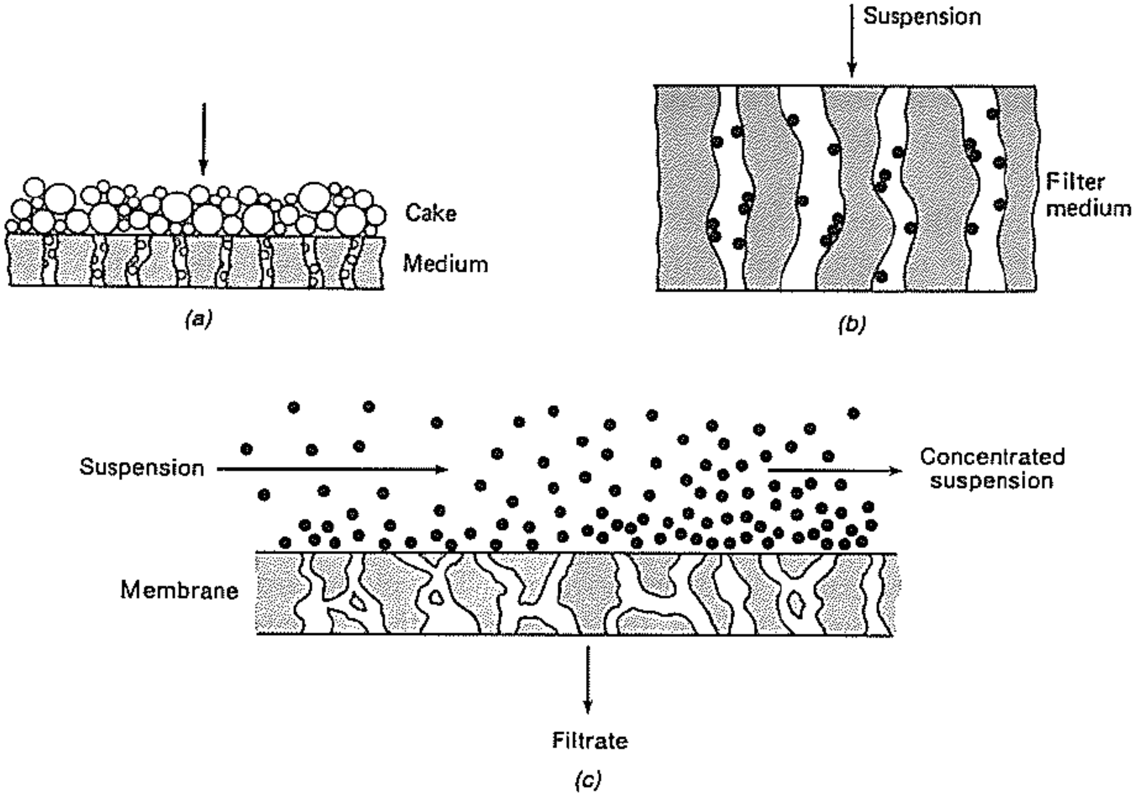
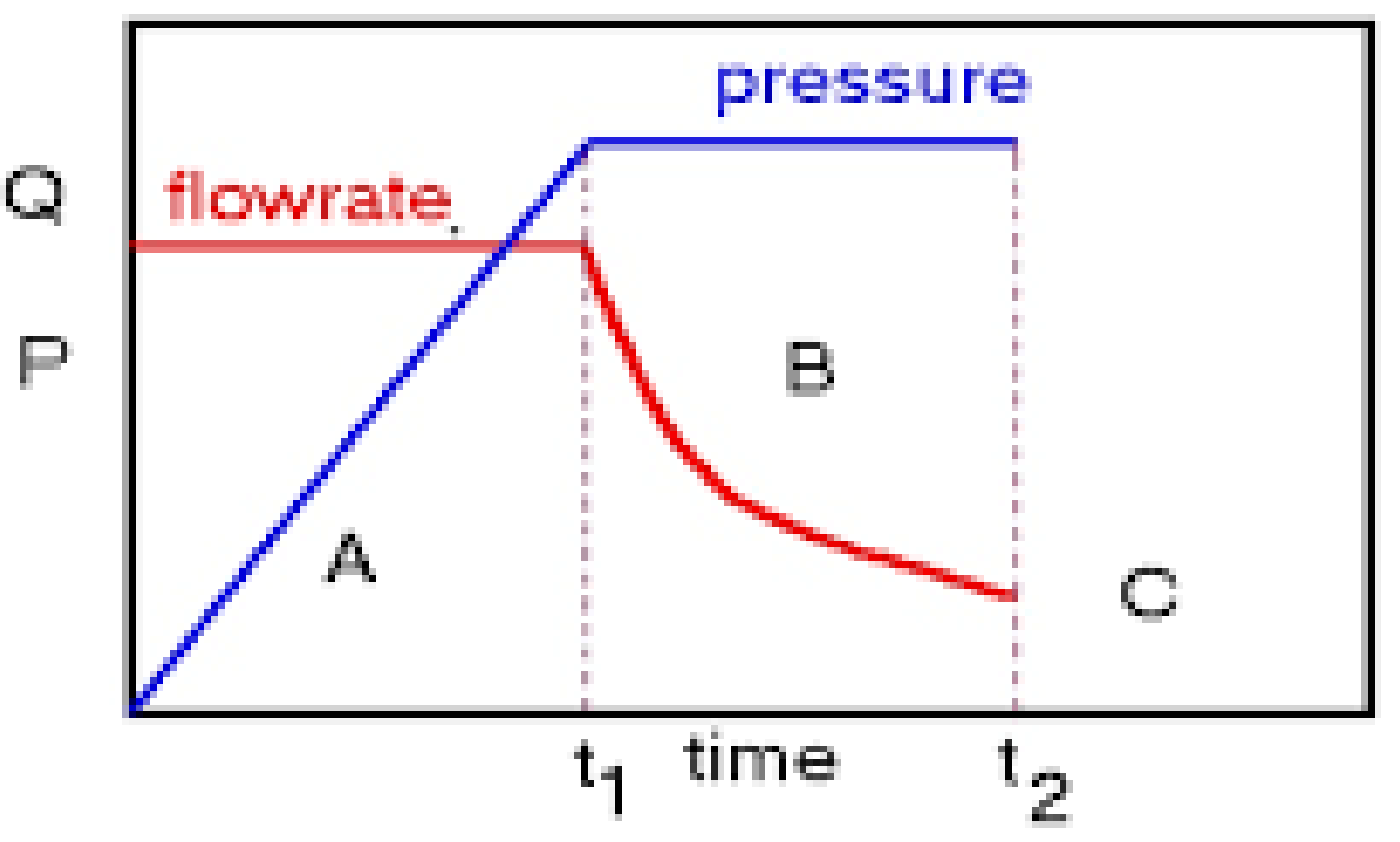


FIGURE 30.4
Mechanisms of filtration: (*a*) cake filter; (*b*) clarifying filter; (*c*) crossflow filter.

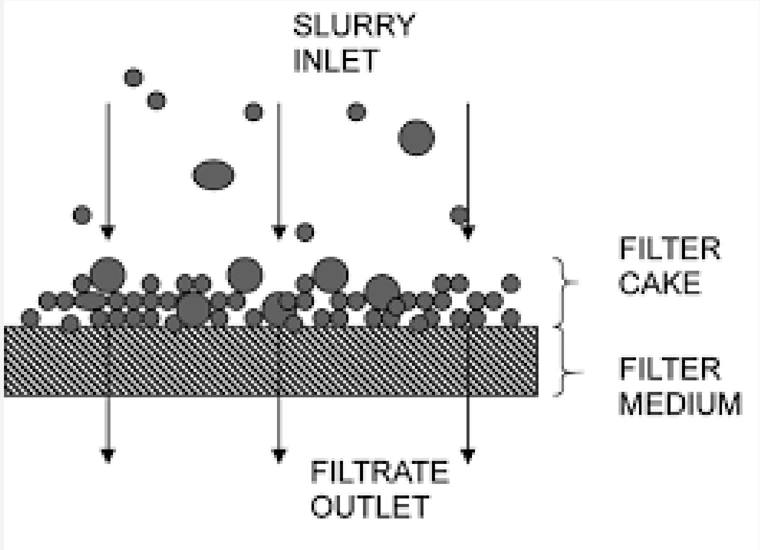
CONSTANT RATE & PRESSURE FILTRATION



Sesame oil cake

PRINCIPLE OF CAKE FILTRATION

- Cake filtration is a process like flow through porous medium.
- During the process, the thickness of solid deposited on the filter medium will start increasing.
- Therefore, flowrate of filtrate will start decreasing.
- The overall pressure drop is the sum of pressure drop across the cake and across the medium.
- $(\Delta p) = (\Delta p_c) + (\Delta p_m)$
- The pressure drop must be increased to keep the flow rate constant.



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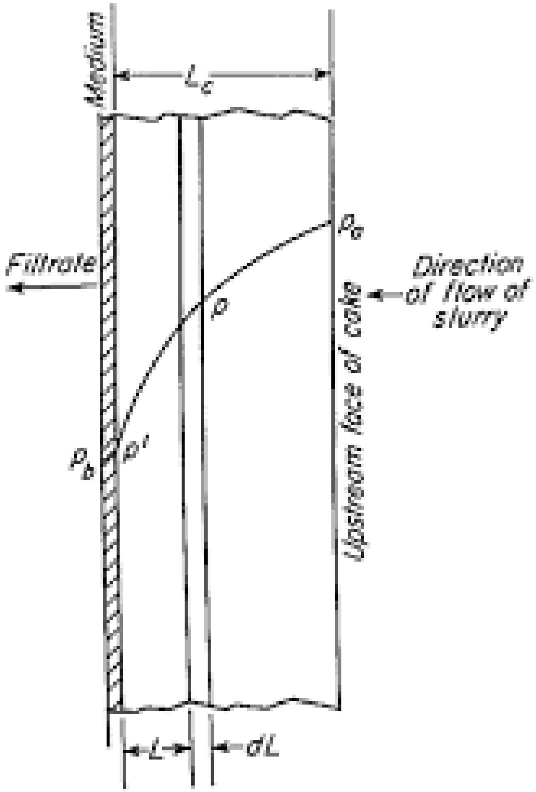
PRESSURE DROP THROUGH FILTER CAKE

- The flow rate through the small thickness dL is very low to ensure laminar flow.
- The flow is assumed to flow through porous medium and pressure drop is given by Kozney-Carman equation:
- $\frac{dp}{dL} = \frac{150\mu u(1-\varepsilon)^2}{\left(\Phi_s D_p\right)^2 \varepsilon^3}$
- Where $u = \frac{dV/dt}{A}$
- V is the volume of filtrate
- A is filter area normal to the direction of flow.



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PRESSURE DROP THROUGH FILTER CAKE

- The filtrate is passing through the entire cake and V/A is constant through all layers and u is independent of L.
- The volume of solids in the layer is $A(1-\varepsilon)dL$ and mass becomes $\mathrm{dm} = \rho_p A(1-\varepsilon)dL$
- $dL = dm/[\rho_p A(1-\varepsilon)]$
- Therefore the pressure drop can be written as
- $\frac{dp}{dL} = \frac{150\mu u(1-\varepsilon)^2}{(\Phi_s D_p)^2 \varepsilon^3}$
- $dp = \frac{150\mu u(1-\varepsilon)^2}{(\Phi_s D_p)^2 \varepsilon^3 [\rho_p A(1-\varepsilon)]} dm = \frac{150\mu u(1-\varepsilon)^2}{(6v_p/s_p)^2 \varepsilon^3 [\rho_p A(1-\varepsilon)]} dm = \frac{k_1 \mu u(1-\varepsilon)}{(v_p/s_p)^2 \varepsilon^3 \rho_p A} dm$

PRESSURE DROP THROUGH FILTER CAKE

- Total pressure drop across the cake:
- $\int_{p'}^{p_a} dp = \int_0^{m_c} \frac{k_1 \mu u (1-\varepsilon)}{\left(v_p/s_p\right)^2 \varepsilon^3 \rho_p A} dm = \Delta p_c$
- For incompressible cake $\Delta p_c = \frac{k_1 \mu u (1-\varepsilon)}{\left(v_p/s_p\right)^2 \varepsilon^3 \rho_p A} m_c$
- Cake resistance $\alpha = \frac{\Delta p_c . A}{\mu u m_c} = \frac{k_1 (1-\varepsilon)}{\left(v_p/s_p\right)^2 \varepsilon^3 \rho_p} = \frac{k_2 (1-\varepsilon)}{\left(\Phi_s D_p\right)^2 \varepsilon^3 \rho_p}$
- The above expression shows that the cake resistance is independent of pressure drop and position in the cake.

PRESSURE DROP THROUGH FILTER CAKE

- Most cakes encountered industrially are not made up of individual rigid particles.
- Practically the slurry contains agglomerates of fine particles and cake properties depend on the properties of those agglomerates.
- The individual geometric shape of particles not affect the cake resistance significantly.
- The presence of flocs makes the flow channel complicated and unpredictable.
- Therefore, such cakes are compressible in nature.
- In compressible cake, the cake resistance varies with distance from the septum. The cake nearest to septum is subjected to greatest compressive for and has lowest void fraction.

PRESSURE DROP THROUGH FILTER CAKE

- Filter medium resistance $R_m = \frac{\Delta p_m}{\mu u}$
- Total pressure drop is $(\Delta p) = (\Delta p_c) + (\Delta p_m)$

$$\Delta p = \frac{\mu u \alpha m_c}{A} + \frac{\mu u}{R_m} = \mu u \left(\frac{\alpha m_c}{A} + R_m\right)$$

- Filter medium resistance varies with higher liquid velocity. It also changes after long operational time.
- But it can be assumed constant during early stages of filtration.

DESIGN EQUATION OF FILTRATION

- Rate of filtration if defined as: $\frac{dV}{dt}$
- Let us assume $m_c =$ Vc and $u = \frac{1}{A}\frac{dV}{dt}$
- Therefore:

$$\Delta p = \mu u \left(\frac{\alpha m_c}{A} + R_m \right)$$

$$or\ \Delta p = \mu \frac{1}{A}\frac{dV}{dt} \left(\frac{\alpha V c}{A} + R_m \right)$$

$$\therefore \frac{dt}{dV} = \frac{\mu}{A(\Delta p)} \left(\frac{\alpha V c}{A} + R_m \right)$$

DESIGN EQUATION OF FILTRATION

$$\frac{dt}{dV} = \frac{\mu}{A(\Delta p)}\left(\frac{\alpha V c}{A} + R_m\right)$$

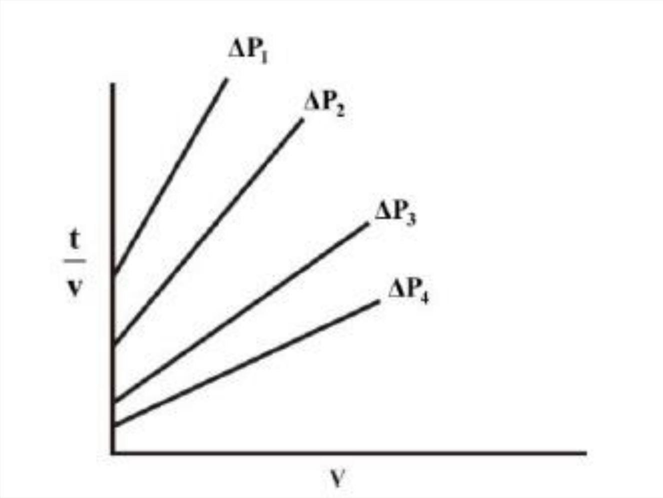
$$0r\ \frac{dt}{dV} = \frac{1}{q} = k_c V + \frac{1}{q_0}$$

Where $\frac{1}{q_0} = \frac{\mu}{A(\Delta p)} R_m$ & $k_c = \frac{\mu \alpha c}{A^2(\Delta p)}$

At constant pressure filtration ??

$$\frac{t}{V} = \frac{k_c}{2} V + \frac{1}{q_0}$$

The equation is useful to calculate the cake resistance and filter medium resistance from experimental data.



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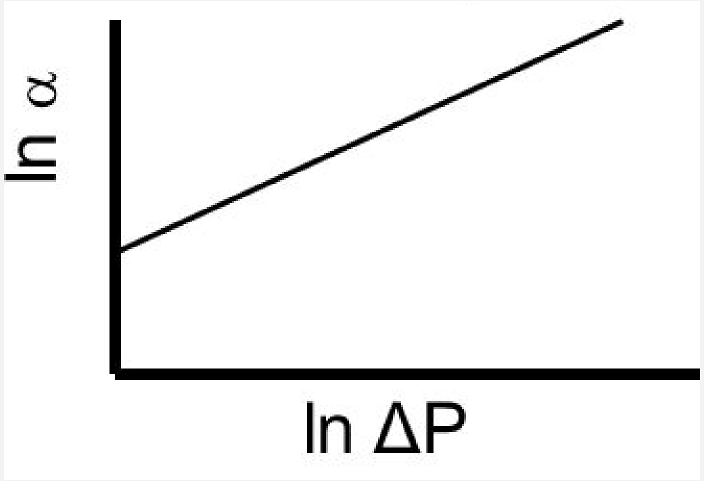
DESIGN EQUATION OF FILTRATION

- For compressible sludge or cake the cake resistance is independent of pressure drop but all cakes formed are compressible at least to some extent.
- Let us assume $\alpha = \alpha_0 (\Delta p)^s$
- Where s is the compressibility coefficient of the cake.
- $s = 0$ for incompressible cake & positive for compressible cake (0.2-0.8)



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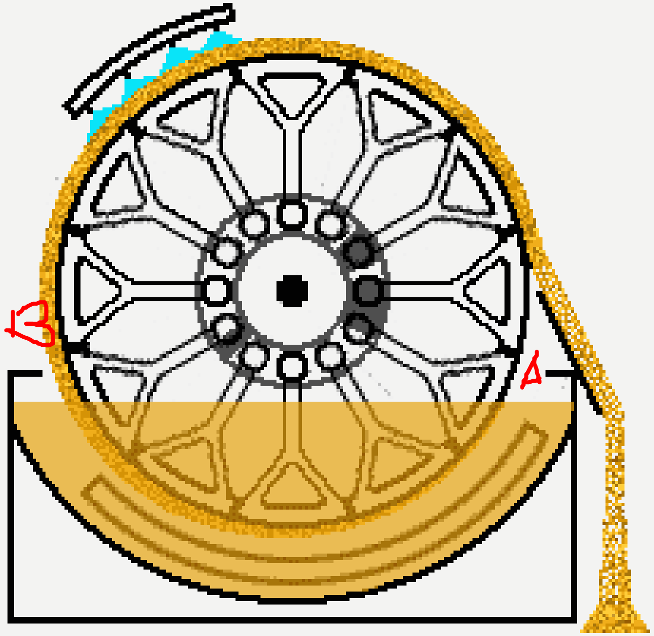
CONTINUOUS FILTRATION



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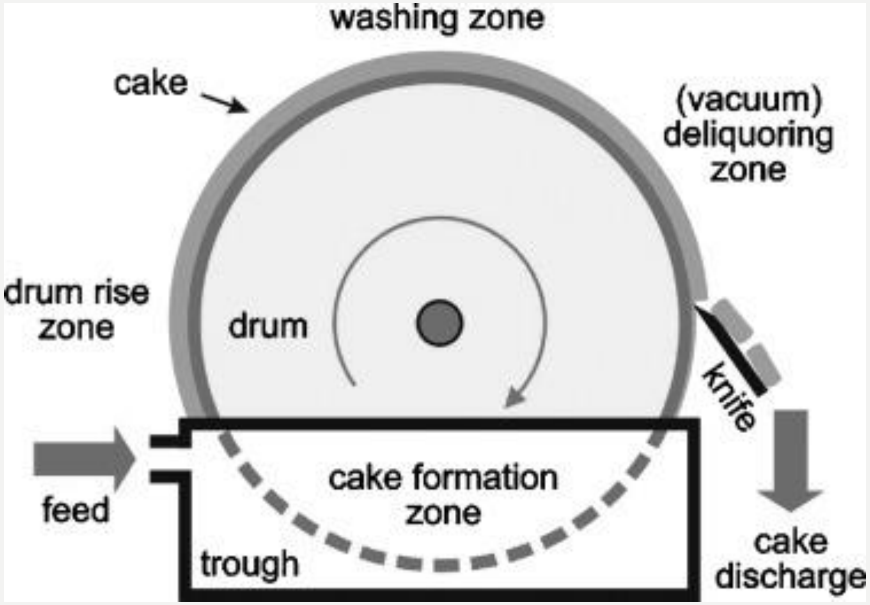

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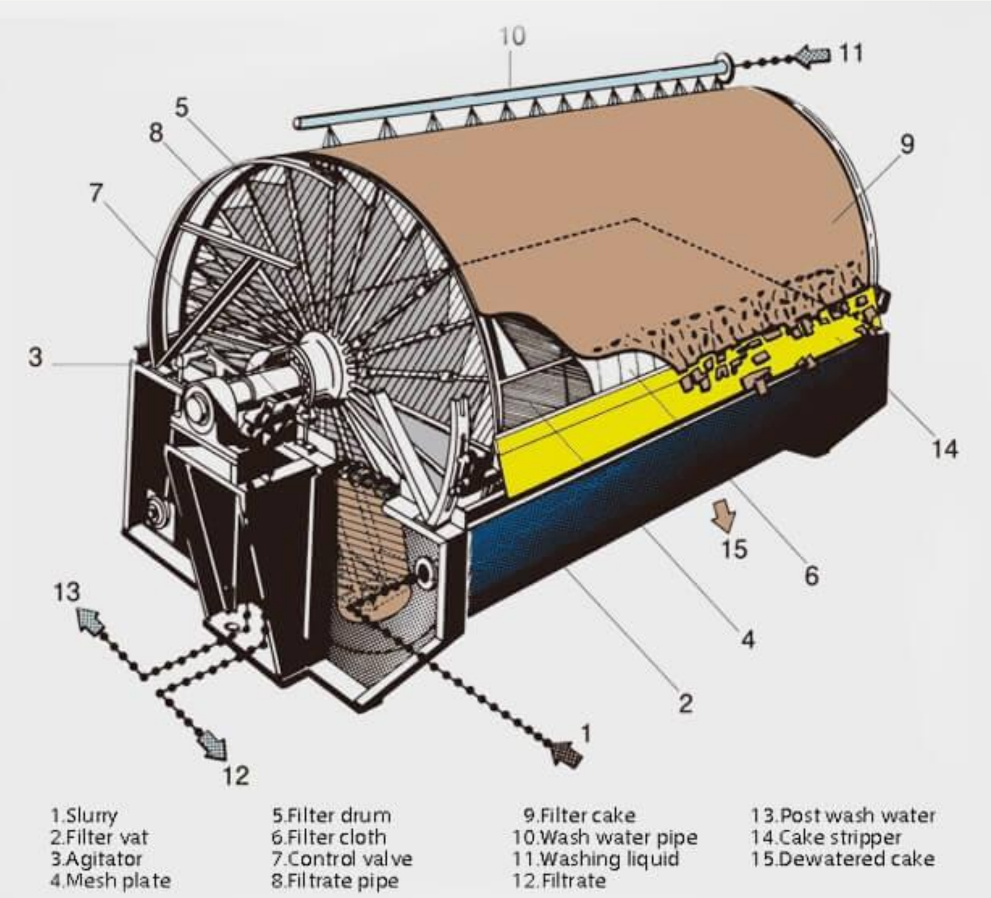
ROTARY DRUM FILTER



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CONTINUOUS FILTRATION

- Continuous filtration in the rotary-drum filter
- Assumptions: feed rate, filtrate rate & cake movement at steady constant rates.
- If t is actual time of filtration then $\boxed{\frac{t}{V} = \frac{k_c}{2}V + \frac{1}{q_0}}$
- Or $V = \frac{\sqrt{\left(\frac{1}{{q_0}^2} - 2k_c t\right)} - \frac{1}{q_0}}{k_c}$
- Where $\frac{1}{q_0} = \frac{\mu}{A(\Delta p)}R_m$ & $k_c = \frac{\mu\alpha c}{A^2(\Delta p)}$

$$\therefore \frac{V}{tA} = \frac{\sqrt{\left(\left(\frac{\mu}{A(\Delta p)}R_m\right)^2 + 2\left(\frac{\mu\alpha c}{A^2(\Delta p)}\right)t\right)} - \left(\frac{\mu}{A(\Delta p)}R_m\right)}{\frac{\mu\alpha c}{A^2(\Delta p)}tA}$$

CONTINUOUS FILTRATION

$$\therefore \frac{V}{tA} = \frac{\sqrt{\left((\frac{\mu}{A(\Delta p)}R_m)^2+2(\frac{\mu\alpha c}{A^2(\Delta p)})t\right)} - (\frac{\mu}{A(\Delta p)}R_m)}{\frac{\mu\alpha c}{A^2(\Delta p)}tA}$$

$$\frac{V}{tA} = \frac{\sqrt{\left((\mu R_m)^2+2\mu(\Delta p)\alpha c t\right)} - \mu R_m}{\mu\alpha c t}$$

$$\frac{V}{\underline{tA}} = \frac{\sqrt{\left((R_m/t)^2+2(\Delta p)\alpha c/\mu t\right)} - (R_m/t)}{\alpha c}$$ ✓

Where $\frac{V}{tA}$ is rate of filtrate collection and A is submerged area of filter.

CONTINUOUS FILTRATION

- If the cycle time is t_c, drum speed n , total filter area A_T and fraction of the drum submerged is f.
- Then actual filtering time $t = f.t_c = \frac{f}{n}$.
- The fraction of drum submerged $f = \frac{A}{A_T}$.
- Rate of cake production $\dot{m}_c = c\frac{V}{t}$
- By substituting $\frac{V}{tA}$ with $\dot{m}_c$ & A_T

$$\frac{V}{tA} = \frac{\dot{m}_c}{A_T.f.c} = \frac{\sqrt{\left((R_m/t)^2+2(\Delta p)\alpha c/\mu\right)} - (R_m/t)}{\alpha c}$$

$$or\ \frac{\dot{m}_c}{A_T} = \frac{\sqrt{\left((R_m f/t)^2+\frac{2f.f(\Delta p)\alpha c}{\mu t}\right)} - (R_m f/t)}{\alpha}$$

$$or\ \frac{\dot{m}_c}{A_T} = \frac{\sqrt{\left((R_m n)^2+\frac{2n.f(\Delta p)\alpha c}{\mu}\right)} - (R_m.n)}{\alpha}$$

CENTRIFUGAL FILTRATION

- Centrifugal filtration works on the principle of centrifuge.
- It is constant pressure filtration process.
- the treatment applies after the cake has been deposited and clear filtrate pass through the cake.

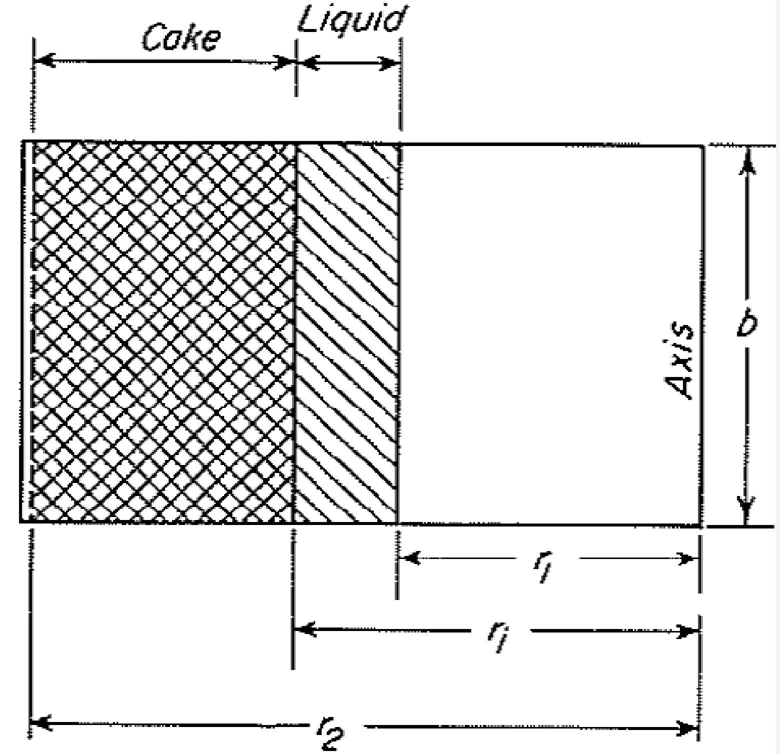


FIGURE 30.18
Centrifugal filter.

CENTRIFUGAL FILTRATION

- Assumptions in centrifugal filtration

1. The gravity force effect is neglected.
2. The pressure drop from centrifugal action is equal to the drag force of liquid through the cake.
3. The flow is laminar, and filter medium resistance is constant.

Therefore, total pressure drop due to centrifugal action is equal to total pressure drop in filtration.

$$\Delta p = \mu u\left(\frac{\alpha m_c}{A} + R_m\right) = \frac{\rho\omega^2(r_2^2 - r_1^2)}{2}$$

Now, $u = \frac{dV/dt}{A} = \frac{q}{A}$

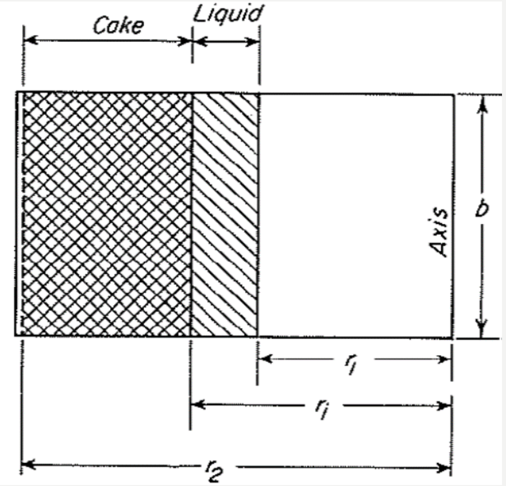
By replacing u by q in 1st equation

$$\mu\frac{q}{A}\left(\frac{\alpha m_c}{A} + R_m\right) = \frac{\rho\omega^2(r_2^2 - r_1^2)}{2}$$

$$or\ q = \frac{\rho A\omega^2(r_2^2 - r_1^2)}{2\mu\left(\frac{\alpha m_c}{A} + R_m\right)} = \frac{\rho\omega^2(r_2^2 - r_1^2)}{2\mu\left(\frac{\alpha m_c}{A^2} + \frac{R_m}{A}\right)}$$

CENTRIFUGAL FILTRATION

$$q = \frac{\rho\omega^2(r_2^2 - r_1^2)}{2\mu\left(\frac{\alpha m_c}{A^2} + \frac{R_m}{A}\right)}$$



- In the above equation the thickness of cake is very small and the area of filter medium and cake (normal to the direction of flow) is constant.
- For significant cake thickness the area will vary with radius.
- Therefore, $A = A_2 = inside\ area\ of\ busket\ or\ centrifuge$

$$\overline{A_L} = \frac{2\pi b(r_2 - r_i)}{ln\frac{r_2}{r_i}}$$

$$\overline{A_a} = \pi b(r_2 + r_i)$$

$$\therefore q = \frac{\rho\omega^2(r_2^2 - r_1^2)}{2\mu\left(\frac{\alpha m_c}{\overline{A_L}.\overline{A_a}} + \frac{R_m}{A_2}\right)}$$

WASHING OF FILTER CAKES

- During filtration, some soluble material may retain by the filter cake .
- A solvent miscible with the filtrate may be used as wash. Generally, water is used as wash.

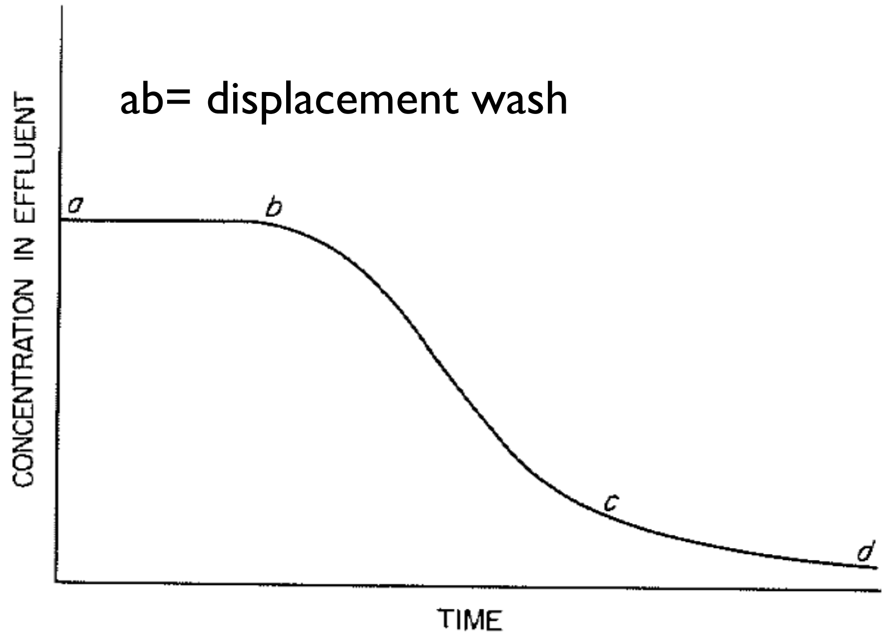
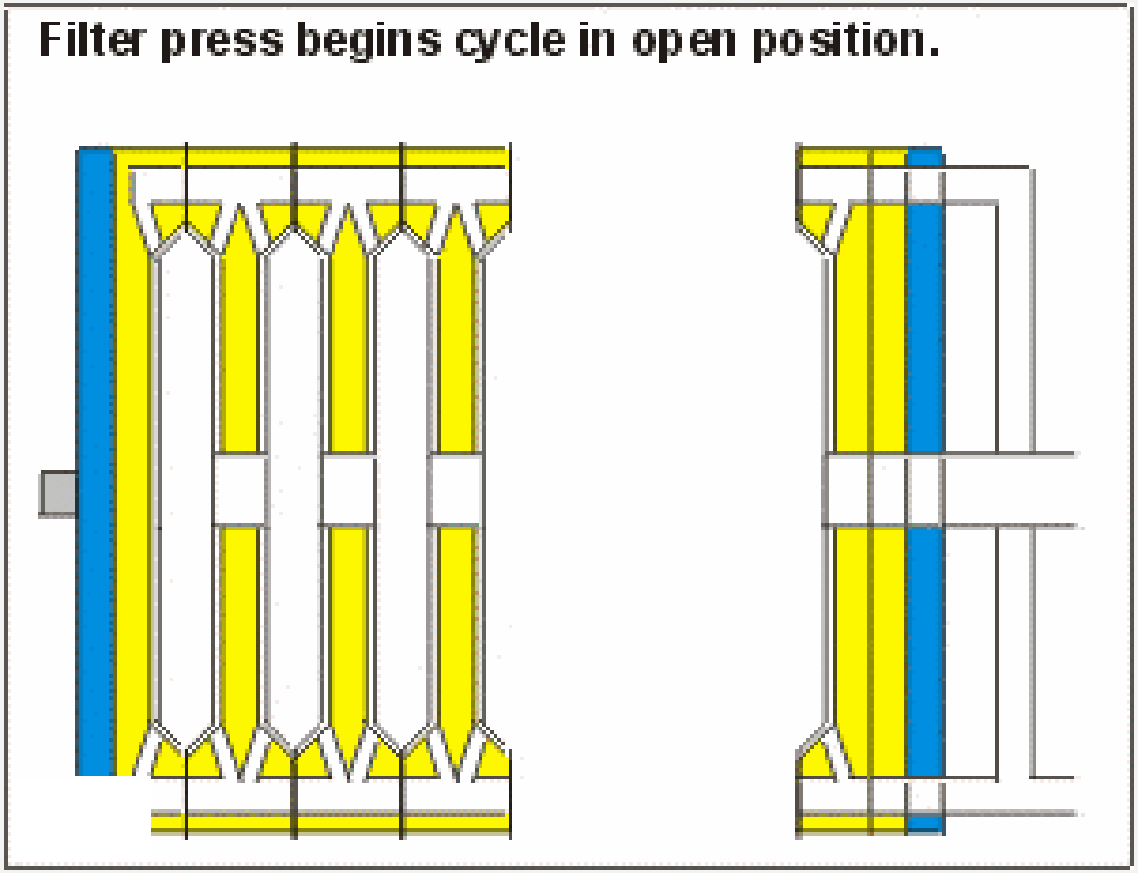


FIGURE 30.19
Washing filter cake.

PLATE & FRAME FILTER PRESS



Filter press begins cycle in open position.

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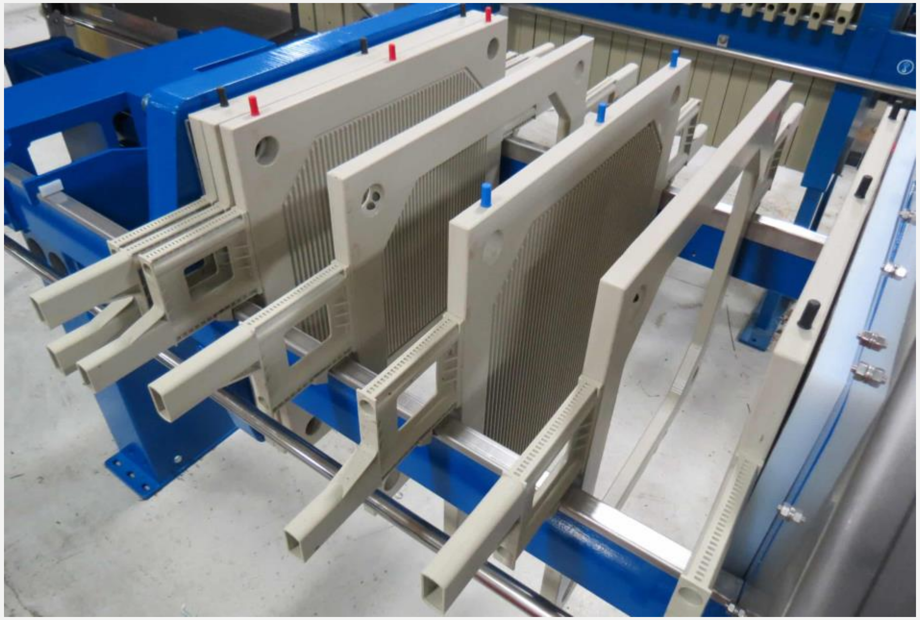
PLATE & FRAME FILTER PRESS



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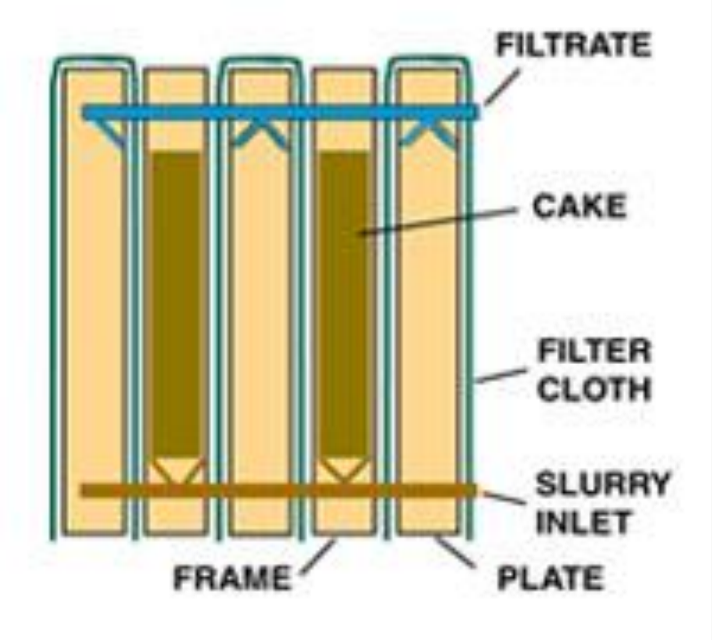

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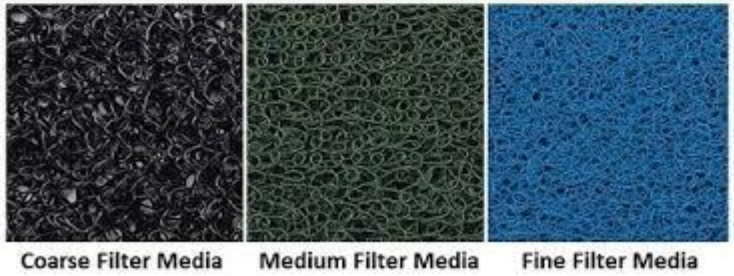
TYPES OF FILTERS

- Filters
  - Discontinuous Pressure filters
    - Plate & frame filter press
    - Shelf & leaf filter (High pr)
    - Automatic belt filter
  - Vacuum filters
    - Buchner funnel (discontinuous) (used for corrosive metal separation)
    - Rotary drum filter (continuous)
    - Horizontal belt filter (continuous) (used for fast & coarse solid separation)
  - Centrifugal filter
    - Suspended batch centrifuge
    - Automatic batch centrifuge
    - Continuous filtering centrifuge

FILTER MEDIUM



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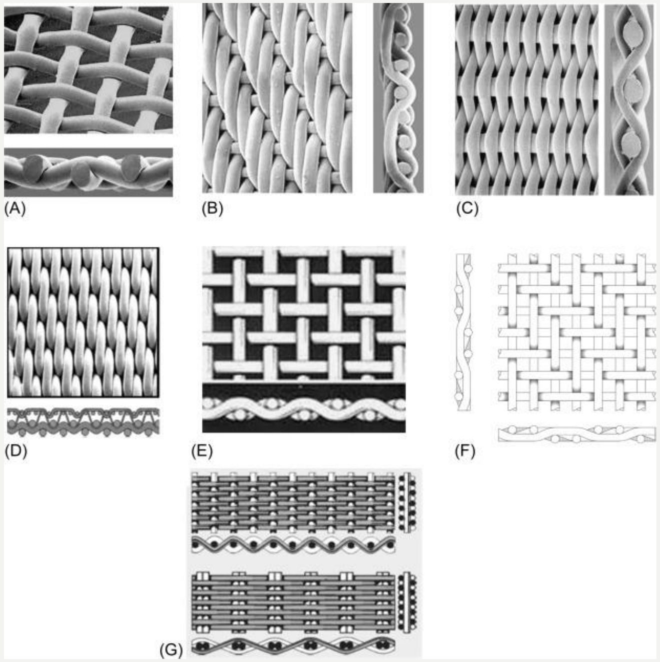
Medium

1. Common filters (canvas cloth)
2. Chemically resistant filters (Synthetic fiber)
3. Corrosive liquid (Woolen cloth, Metal cloth, Glass cloth)



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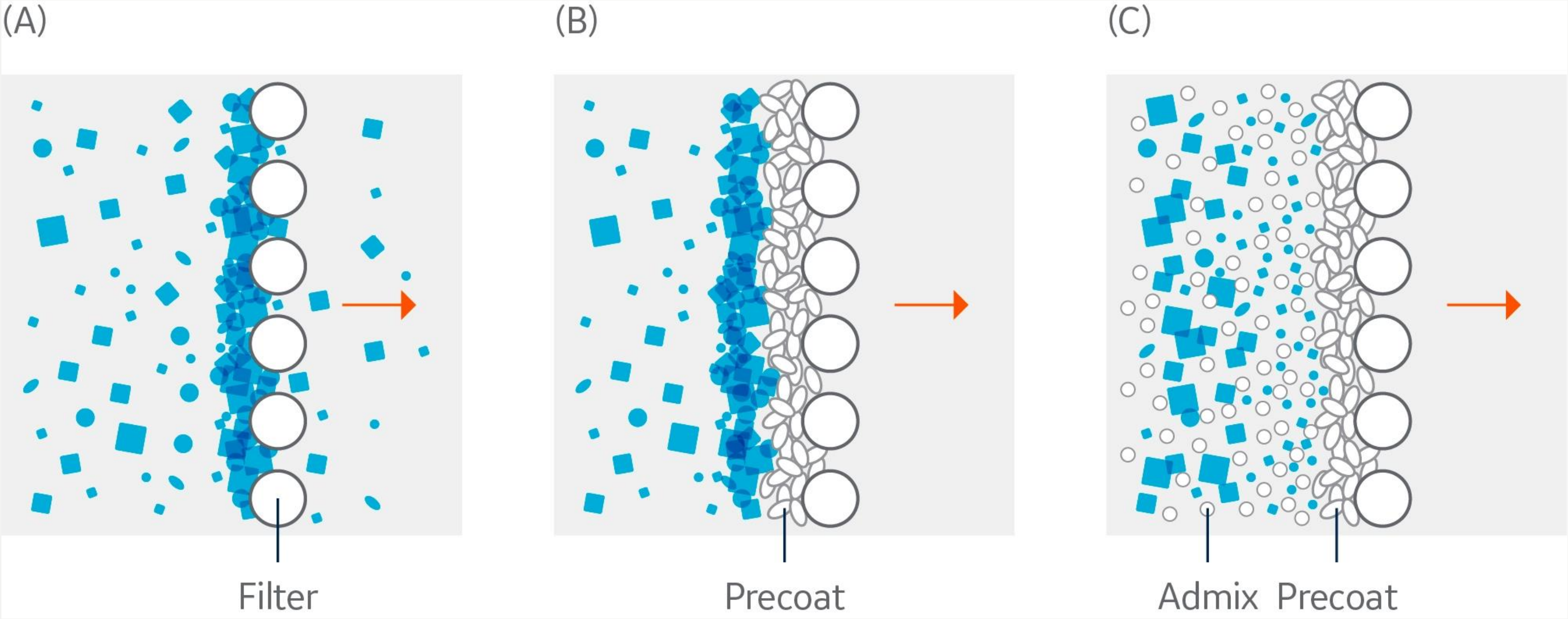
FILTER AIDS



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FILTER AIDS

- Filter aids are slimy or very fine solid that form an impermeable & dense cake. It increases the porosity of cake and filtration occurs at reasonable rate. Example: diatomaceous silica, perlite, purified wood cellulose or other inter porous solid.
- Precoating of filter are also used on medium and scraped off in regular interval. It prevents the plugging of medium by gelatinous solids.

STEPS OF FILTRATION

1. Draining the liquor
2. Filtration
3. Filling with wash water
4. Washing
5. Draining if wash water
6. Opening, dumping & reassembling
7. Filling with slurry

NUMERICAL

- A constant pressure filtration test gave data that can fit an expression dt/dV = 9.3 V + 8.5; (t in seconds, V in liters). If the resistance of the filter medium is assumed unaffected with pressure drop and the compressibility coefficient of the cake is 0.3, what will be the time taken for the collection of 3.5 liters of filtrate at a filtration pressure twice that used in the test.
- Solution:

$$\frac{dt}{dV} = \frac{\mu}{A(\Delta p)}\left(\frac{\alpha V c}{A} + R_m\right) = 9.3V + 8.5$$

And $\alpha = \alpha_0(\Delta p)^s$

therefore $\frac{\mu}{A(\Delta p)}\frac{\alpha c}{A} = \frac{\alpha_0(\Delta p)^{s-1}c\mu}{A^2} = 9.3$

$$\frac{\mu R_m}{A(\Delta p)} = 8.5$$

NUMERICAL

Now, if pressure drop is doubled

$$\frac{\mu}{A(\Delta p)}\frac{\alpha c}{A}=\frac{\alpha_0(\Delta p)^{s-1}c\mu}{A^2}=9.3\times(2)^{0.3-1}=5.72$$

$$\frac{\mu R_m}{A(\Delta p)}=\frac{8.5}{2}=4.25$$

$$\frac{dt}{dV}=\frac{\mu}{A(\Delta p)}\left(\frac{\alpha Vc}{A}+R_m\right)=5.72V+4.25$$

$$t=5.72\frac{V^2}{2}+4.25V$$

$$t=5.72\frac{(3.5)^2}{2}+4.25(3.5)=49.93\mathrm{sec}$$

NUMERICAL

- A pressure filter is operated in the constant rate mode to yield 10 m3 in the first ten minute, as the pressure increases from zero. In the next 20 minutes the filtration was continued at constant pressure, after which it was stopped. Assume filter medium resistance is negligible and the cake is incompressible.
- a) Estimate the total volume of filtration obtained.
- b) Determine washing time if the volume of wash liquid equals the volume of filtrate obtained.

NUMERICAL

- Solution: (a)

$$\frac{dt}{dV} = \frac{\mu\alpha c}{A^2(\Delta p)}V$$

In 1st 10mins V=10m3

$$\frac{10}{10} = \frac{\mu\alpha c}{A^2(\Delta p)}10$$

$$or\ \frac{\mu\alpha c}{A^2(\Delta p)} = 0.1$$

In next 20mins

$$\frac{dt}{dV} = \frac{\mu\alpha c}{A^2(\Delta p)}V = 0.1V$$

$$\therefore \int_{10}^{30} dt = \int_{10}^{V} 0.1V\, dV$$

$$or\ 20 = 0.1\frac{V^2 - 10^2}{2}$$

$$\therefore V = \sqrt{500} = 22.36\, m^3$$ **ans.**

Solution: (b)

The volume of wash liquid = the volume of filtrate obtained=$22.36\, m^3$

Washing rate = rate of filtration =

$$\left(\frac{dV}{dt}\right)_{t=30min} = \frac{1}{0.1V} = \frac{1}{0.1\times 22.36}\, m^3/min$$

$$\therefore Washing\ time = \frac{22.36\, m^3}{\frac{1}{0.1\times 22.36} m^3/min} =$$

$50mins$ ans

NUMERICAL

- A filtration is carried out for 10 min at a constant rate in a leaf filter and thereafter it is continued at constant pressure. This pressure is that attained at the end of the constant rate period. If one quarter of the total volume of the filtrate is collected during the constant rate period, what is the total filtration time? Assume that the cake is incompressible, and the filter medium resistance is negligible.
- Solution:

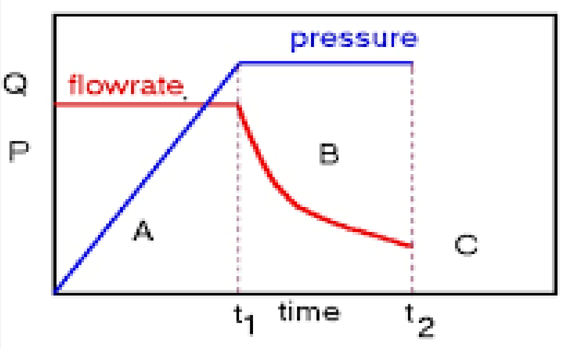
At constant rate

$$\frac{dt}{dV} = \frac{\mu \alpha c}{A^2(\Delta p)} V$$

In 1st 10mins V

$$\frac{10}{V} = \frac{\mu \alpha c}{A^2(\Delta p)} V$$

$$or\ \frac{\mu \alpha c}{A^2(\Delta p)} V^2 = 10$$



NUMERICAL

At constant Pressure

$$\frac{dt}{dV} = \frac{\mu\alpha c}{A^2(\Delta p)} V$$

$$\therefore \int_{10}^{t} dt = \int_{V}^{4V} \frac{\mu\alpha c}{A^2(\Delta p)} V\, dV$$

$$or \int_{10}^{t} dt = \frac{\mu\alpha c}{A^2(\Delta p)} \int_{V}^{4V} V\, dV = \frac{10}{V^2} \frac{(4V)^2 - (V)^2}{2}$$

$$or (t - 10) = 75$$

$$or \quad t = 85 mins\ \boldsymbol{ans}.$$

NUMERICAL

- It is required to design a rotary filter with 30% submergence fed with 3.3 m^3/h of a slurry containing 236 kg solids per m^3 of filtrate. The absolute pressure maintained during filtration is 68 kPa and the mean specific cake resistance is 5×10^{10} m/kg . The speed of rotation of drum = 0.2 rpm. Calculate the rate of dry cake production.
- Solution:
- The fraction of drum submerged $f = \frac{A}{A_T} = 0.3$.
- Drum speed $n = 0.2\, rpm = \frac{0.2}{60} rps$
- $t_c = \frac{60}{0.2} = 300\ s$
- Actual filtering time $t = f.t_c = \frac{f}{n} = 90 sec$.

- $\frac{\dot{m}_c}{A_T} = \sqrt{\left(\frac{2n.f(\Delta p)c}{\mu\alpha}\right)} = \sqrt{\left(\frac{2(0.2/60).(0.3)(68000)\ 236}{(0.001)(5\times10^{10})}\right)} = 0.025kg/(m^2.s)$
- Where $\dot{m}_c = Vc = \frac{3.3\times236}{3600} = 0.216\ kg/s$ (rate of dry cake production)
- $A_T = \frac{\dot{m}_c}{0.025} = \frac{0.216}{0.025} = 8.53m^2$