Filtration

Principles, theory and operation

Filtration Process

Introduction:

- **Cake filtration is widely used in industry to separate solid particles from suspension in liquid.**
- **Cake filtration is a common application for the flow through packed beds of particles.**

- **Filtration process involves the build up of a bed or 'cake' of particles on a porous surface known as the filter medium, which commonly takes the form of a woven fabric. The pore size of the medium is less than the size of the particles to be filtered.**

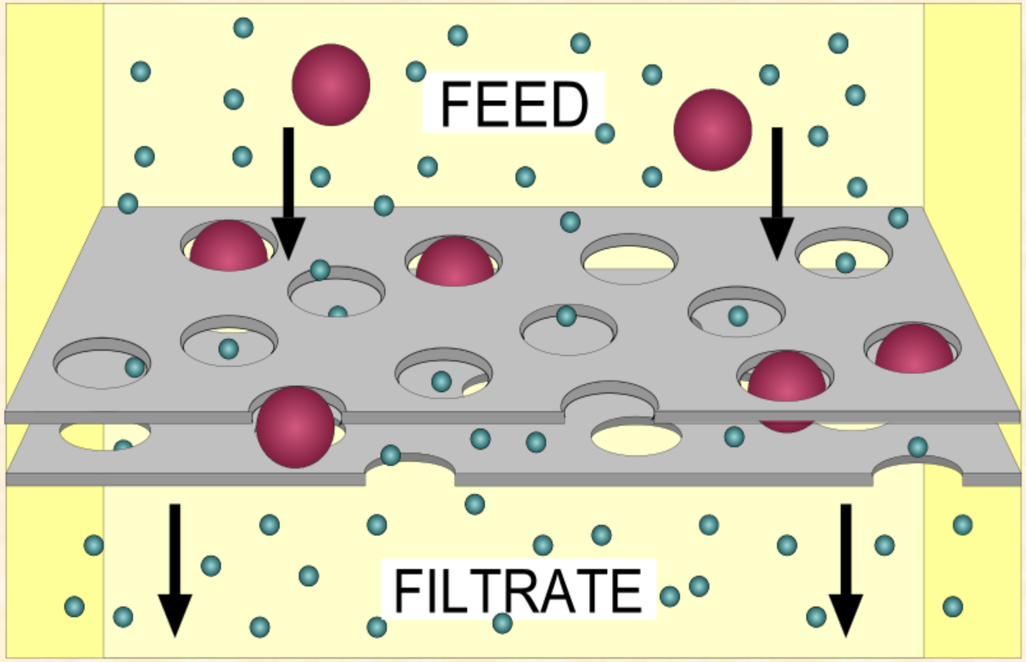
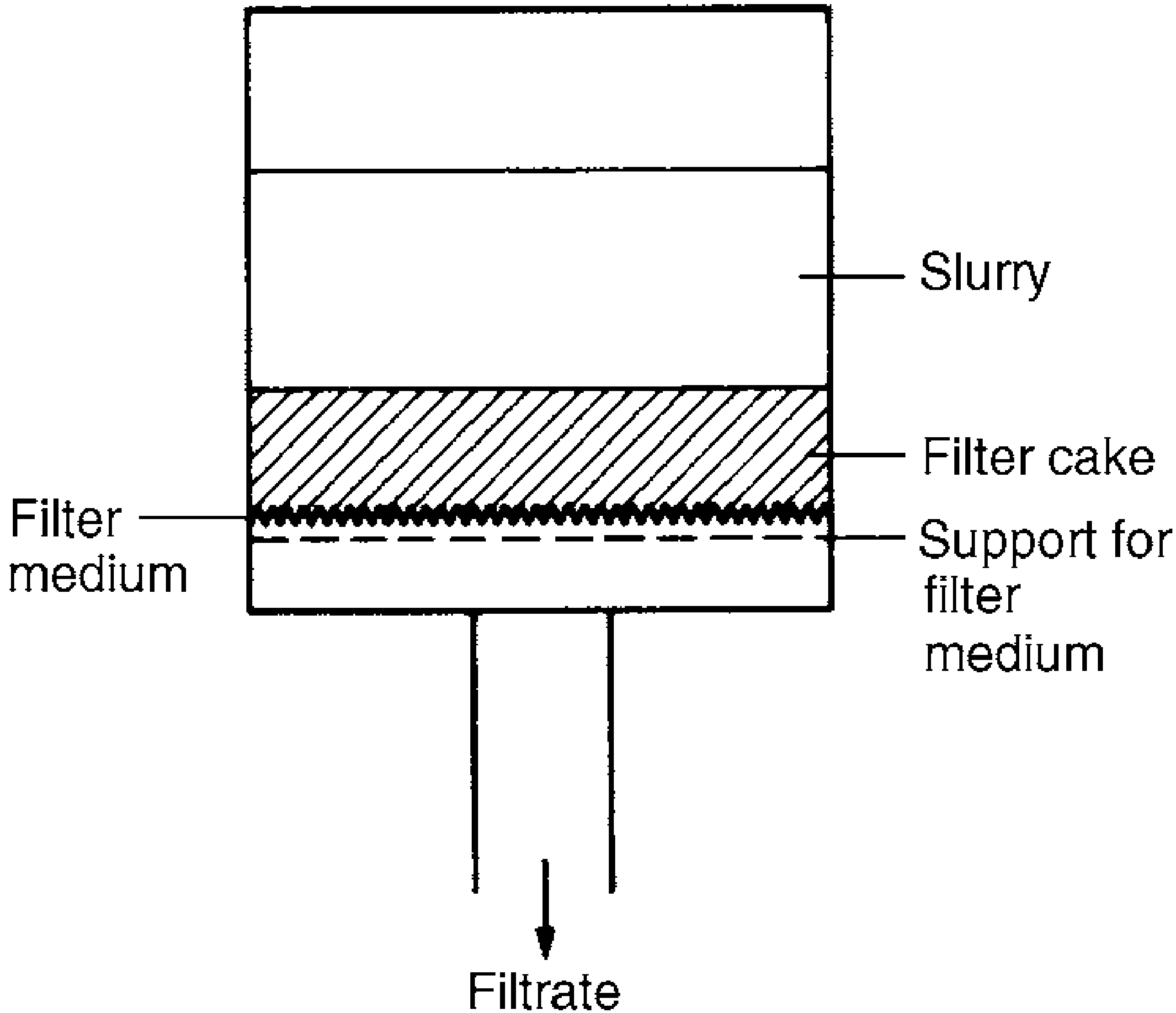


Diagram of simple filtration: oversize particles in the feed cannot pass through the lattice structure of the filter, while fluid and small particles pass through, becoming filtrate

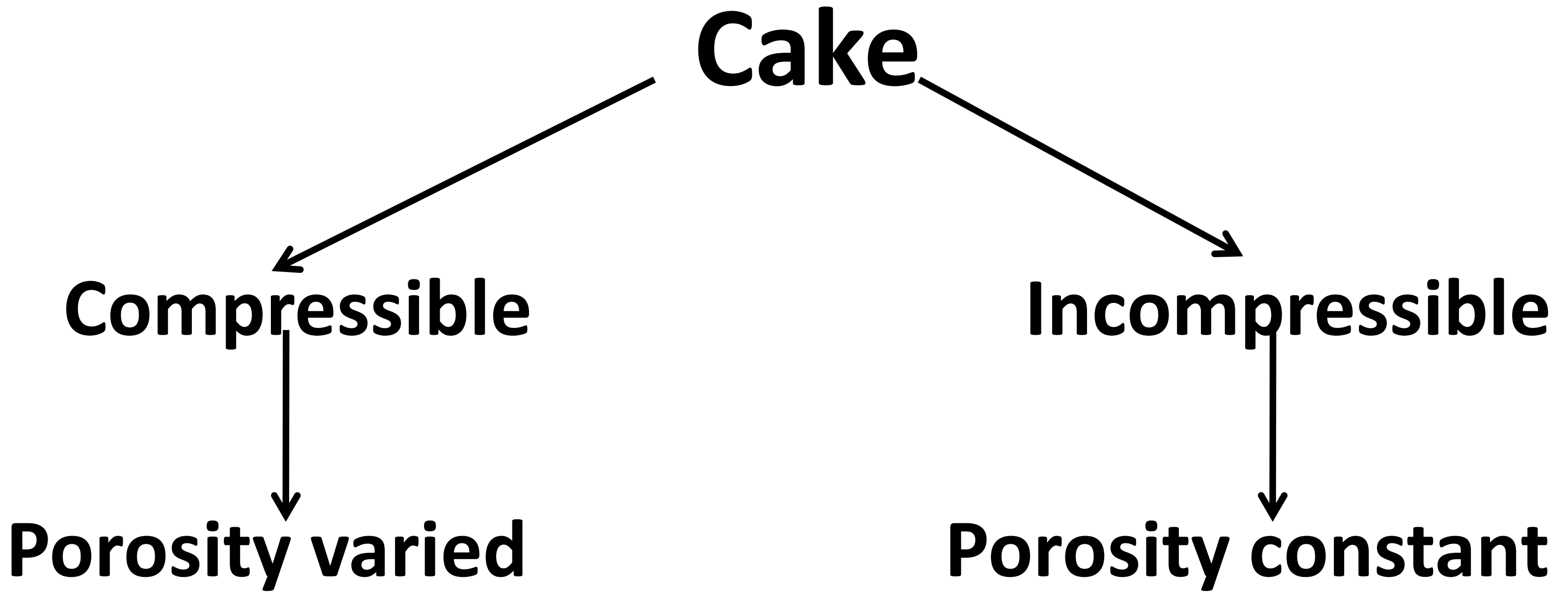
- **In general, filtration process can be analyzed in terms of the flow of fluid through a packed bed of particles, the depth of which is increasing with time. The voidage of cake may be changed with time " compressible cake" but we can assume, in some cases, the cake voidage is constant " incompressible cake".**

Principle of filtration



Summary & Definitions

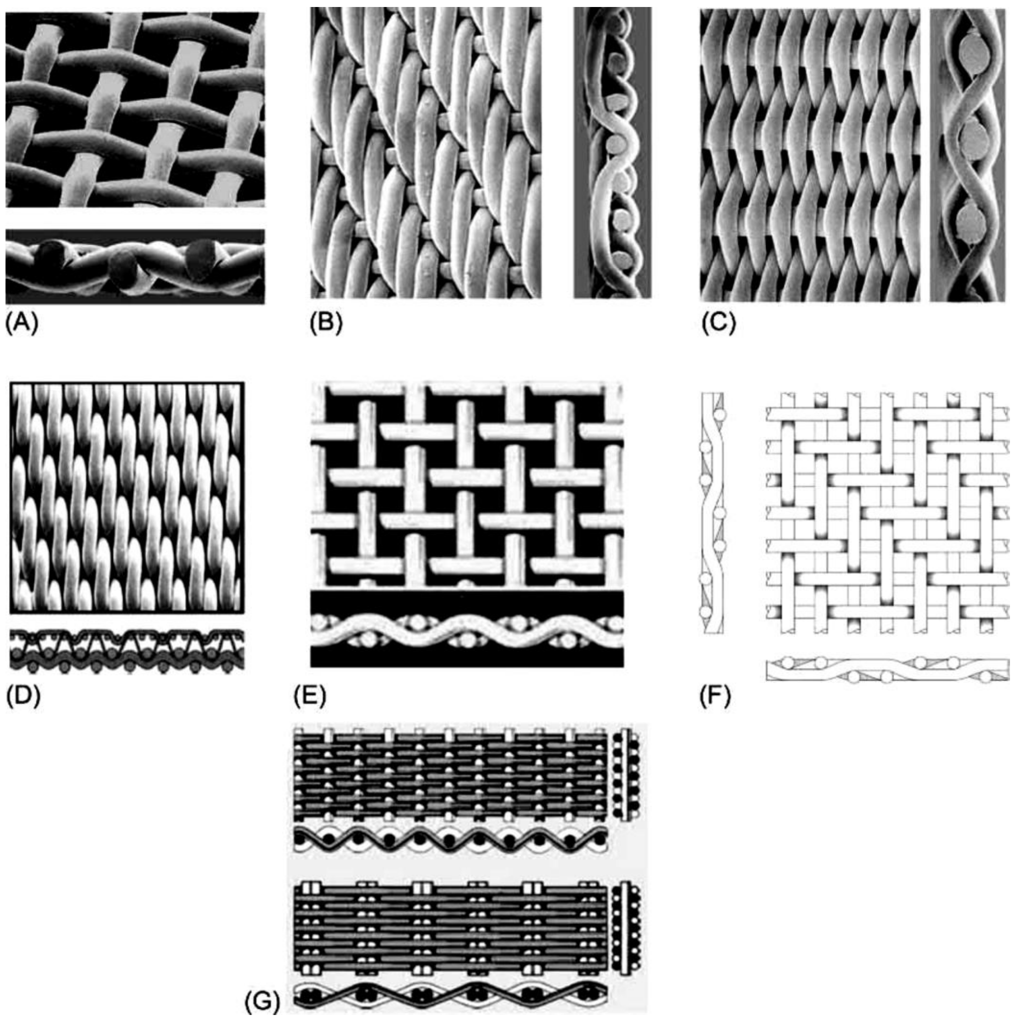
- **Filtration is a separation of solid particles from liquid with the aid of a semi-permeable medium, which retains the solids and allows the liquid to pass through.**
- **Classification of equipment: gravity, pressure and vacuum filters.**
- **Filter cake: a bed of solid particles.**
- **Filtrate: liquids which pass through the filter medium.**


Cake
Compressible
Incompressible
Porosity varied
Porosity constant

Filter media $\equiv$ Septum

a) it must retain solids
b) it must not plug
c) it must be strong enough chemically and physically to withstand different operating conditions.
d) it must allow the cake to be removed cleanly and completely.
e) it must be cheap.

Typical filter media



(A) plain, square weave,
(B) twill weave,
(C) plain, reverse Dutch,
(D) Double layer weave,
(E) plain weave in metal media,
(F) twilled weave in metal media,
(G) twilled weave in metal media

Filter aids

Substances used to increase the porosity of solid cake in order to permit the liquid to pass at a reasonable rate. Filter aids such as diatomaceous earth, asbestos, purified wood cellulose or other inert porous solids.

<u>Note:</u> The support of media affects the way of the cake growth.

factors to be considered when selecting equipment and operating

- The properties of the fluid, particularly its viscosity, density, and corrosive properties.
- The nature of the solid—its particle size and shape, size distribution, and packing characteristics.
- The concentration of solids in suspension.
- The quantity of material to be handled, and its value.
- Whether the valuable product is the solid, the fluid, or both.
- Whether it is necessary to wash the filtered solids.
- Whether the feed liquor may be heated.

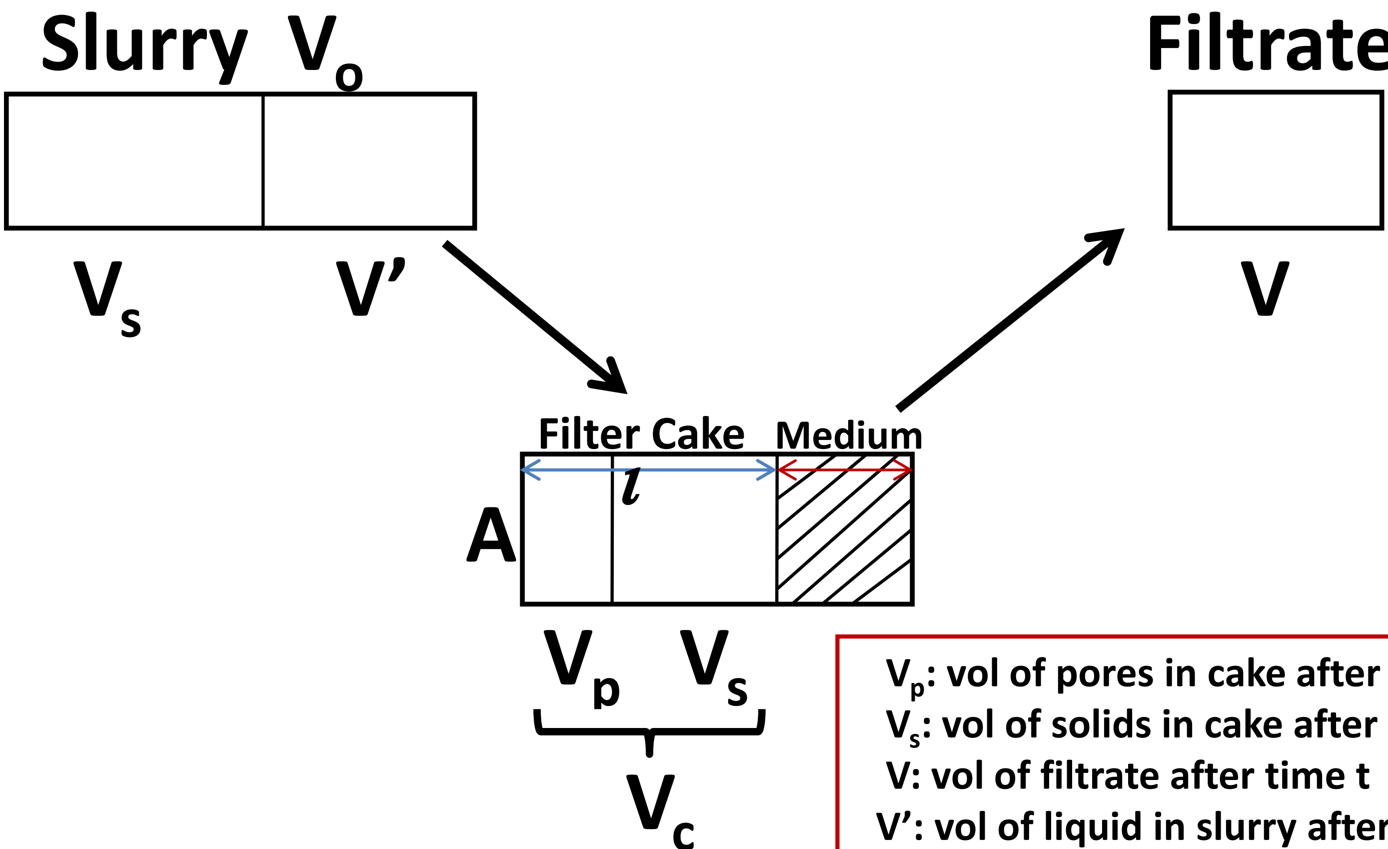
Theory of filtration

- **Filtration is similar to the flow of a fluid through a granular bed. The only difference is that the thickness of cake is growing with time.**
- **There are two operating conditions:**

  ~ filtration pressure is constant whilst the flow of filtrate disappears with time.

  ~ the flow of filtrate is constant whilst the pressure increases with time.

Process of filtration



V_p: vol of pores in cake after time t

V_s: vol of solids in cake after time t

V: vol of filtrate after time t

V’: vol of liquid in slurry after time t

V_c: vol of cake formed after time t

l: thickness of filter cake

- **Since the particles forming the filter cake are very small, as well as the flow of filtrate through the cake is very slow, laminar constrains are dominant. Hence, Carman-Kozeny equation can be applied:**

$$u = \frac{1}{A}\frac{\mathrm{dv}}{\mathrm{dt}} = \frac{1}{5}\frac{e^3}{(1-e)^2 S^2}\frac{(-\Delta P)}{\mu\, l} \qquad (1)$$

Where

ΔP: applied pressure difference.

S: sp. surface area of particles.

Assume e = constant 'incompressible cake'

$$\therefore \quad e^3 \big/ 5(1-e)^2 S^2 \equiv \text{Constant} = 1/r$$

$$\therefore \quad \frac{1}{A}\frac{dV}{dt} = \frac{(-\Delta P)}{r\,\mu\,l} \qquad (2)$$

r represents a property of particles.

r is called *<u>specific resistance</u>* of cake which depends on e and S. It is constant for incompressible cake, but it depends on the rate of deposition, nature of particles and the force between the particles.

Typical values of specific resistance

Material	Upstream Filtration Pressure (kN/m^2)	r(m^{-2})
High-grade kieselguhr	–	2×10^{12}
Ordinary kieselguhr	270	1.6×10^{14}
	780	2.0×10^{14}
Carboraffin charcoal	110	4×10^{13}
	170	8×10^{13}
Calcium carbonate	270	3.5×10^{14}
(precipitated)	780	4.0×10^{14}
Ferric oxide (pigment)	270	2.5×10^{15}
	780	4.2×10^{15}
Mica clay	270	7.5×10^{14}
	780	13×10^{14}
Colloidal clay	270	8×10^{15}
	780	10×10^{15}
Gelatinous	270	5×10^{15}
magnesium hydroxide	780	11×10^{15}
Gelatinous aluminium	270	3.5×10^{16}
hydroxide	780	6.0×10^{16}
Gelatinous ferric	270	3.0×10^{16}
hydroxide	780	9.0×10^{16}
Thixotropic mud	650	2.3×10^{17}

Note

r sometimes referred to as the ‘permeability of cake’.

Material balance over the solid in cake and slurry

Mass of solids in cake = (1-e) Al ρ_s

Mass of liquid in cake = e A lρ

Assume J is the mass fraction of solids in suspension, then J/(1-J) is the solid to liquid ratio .

$$\therefore \quad (1-e)\,Al\,\rho_S = (V + eAl)\rho\frac{J}{1-J} \qquad (4)$$

$$\therefore \quad (1-J)(1-e)Al\rho_S = J\rho V + eAl\rho J \qquad (5)$$

$$\therefore \quad l = \frac{JV\rho}{A\{(1-J)(1-e)\rho_S - Je\rho\}} \qquad (6)$$

OR

$$V = \frac{Al\{(1-J)(1-e)\rho_S - Je\rho\}}{\rho J} \qquad (7)$$

Assume *v* is the vol of cake per unit vol of filtrate

v=lA/V *or* *l=vV/A* (8)

Combining equations 6 and 8

$$\therefore \quad v = \frac{J\rho}{(1-J)(1-e)\rho_S - Je\rho} \qquad (9)$$

Substituting for / in eq. 2

$$\frac{1}{A}\frac{dV}{dt} = \frac{(-\Delta P)}{r\,\mu}\frac{A}{vV} \qquad (10)$$

OR

$$\frac{dV}{dt} = \frac{(-\Delta P)}{r\,\mu}\frac{A^2}{vV} \qquad (11)$$

For constant rate of filtration

$$\frac{dV}{dt} = \text{constant} = \frac{V}{t} \qquad (12)$$

$$\therefore \qquad \frac{V}{t} = \frac{A^2(-\Delta P)}{r\mu\, vV} \qquad (13)$$

OR

$$\frac{t}{V} = \frac{r\mu\, vV}{A^2(-\Delta P)} \qquad (14)$$

Where (-ΔP) is directly proportional to V.

For a filtration at constant pressure difference

$$\therefore \qquad \frac{dV}{dt} = \frac{(-\Delta P)}{r\,\mu}\frac{A^2}{vV}$$

$$\int_0^V V\,dV = \frac{(-\Delta P)}{r\,\mu}\frac{A^2}{v}\int_0^t dt$$

$$\frac{V^2}{2} = \frac{(-\Delta P)}{r\,\mu}\frac{A^2}{v}\,t \qquad (15)$$

$$OR$$

$$\frac{t}{V} = \frac{r\;\mu\;v}{2(-\Delta P)A^2}V \qquad (16)$$

For constant pressure filtration, there is a linear relation between V^2 and t or t/V and V.

Note

The pressure difference, (-ΔP), is initially increased until a certain limit. Suppose it takes time t_1 with vol of filtrate V_1 to reach this limit. Then the integration of eq. 15 becomes:

$$\frac{1}{2}(V^2 - V_1^2) = \frac{(-\Delta P)}{r\mu}\frac{A^2}{v}(t - t_1) \qquad (17)$$

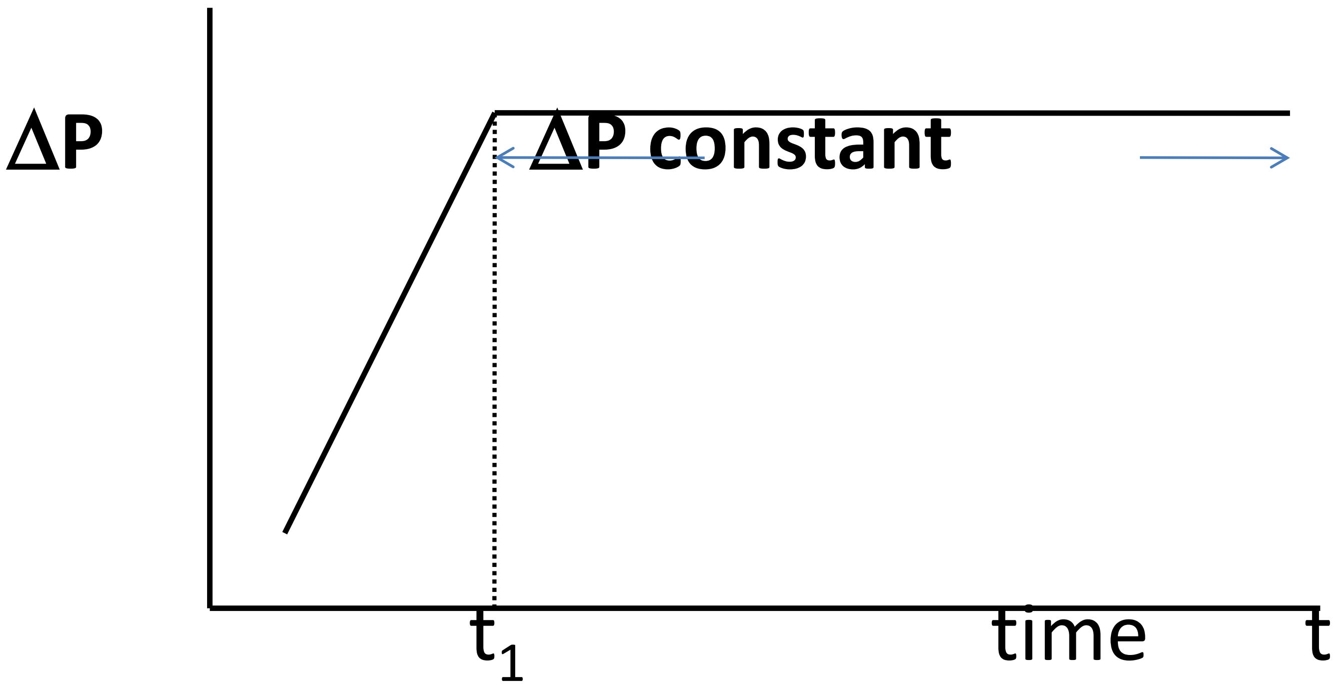
$$OR$$

$$\frac{t - t_1}{V - V_1} = \frac{rv\mu}{2A^2(-\Delta P)}(V - V_1) + \frac{rv\mu V_1}{A^2(-\Delta P)} \qquad (18)$$

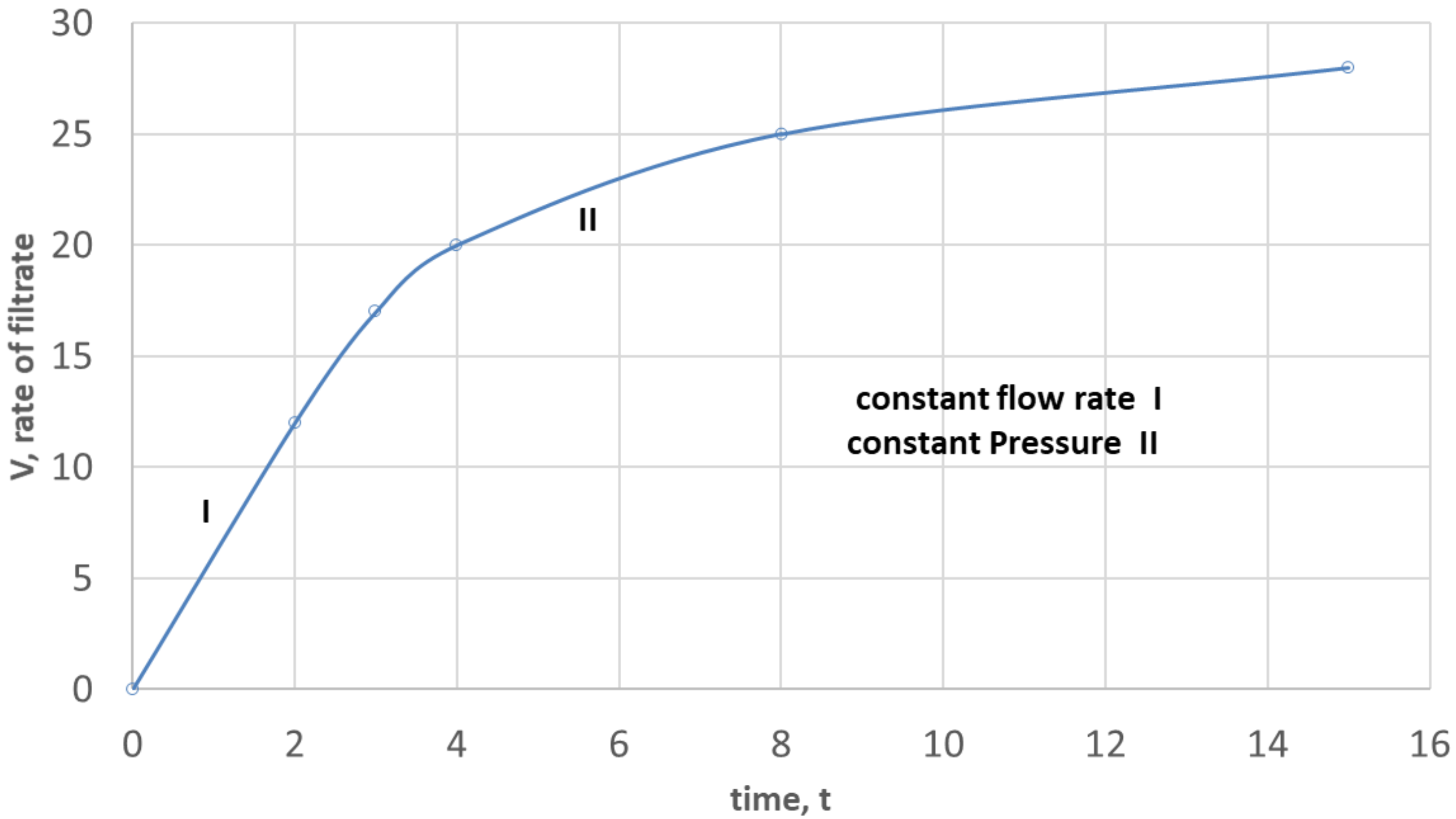
Where $t-t_1$: time of cons. Pressure filtration

$V-V_1$: volume of filtrate at cons. Pressure filtration

There is a linear relation between $(t-t_1)/(V-V_1)$ and $V-V_1$



2 Filtration stages I & II



Flow of liquid through the cloth

$$\therefore \quad \frac{1}{A}\frac{dV}{dt} = \frac{(-\Delta P)}{r\,\mu\,l} \qquad (19)$$

There are two resistances;

- Resistance due to cloth and
- Resistance due to initial layer of cake

Assume the thickness of filter cloth and the initial layer of cake to be equivalent to thickness ‘L’ of cake as deposited at a later stage in the operation. Hence eq. 1 becomes:

$$\frac{1}{A}\frac{dV}{dt} = \frac{(-\Delta P)}{r\mu(l+L)} \qquad (20)$$

where $(-\Delta P)$ *is the pressure drop across the cake plus the cloth.* *Substituting eq.(8) into eq. (20)*

l=vV/A

$$\therefore \quad \frac{dV}{dt} = \frac{A(-\Delta P)}{r\mu(\frac{Vv}{A}+L)} = \frac{A^2(-\Delta P)}{vr\mu(V+\frac{LA}{v})} \qquad (21)$$

<u>For constant rate filtration</u>

Equation 3 can be integrated.

$$\frac{dV}{dt} = \text{constant} = \frac{A^2(-\Delta P)}{vr\mu(V + \frac{LA}{v})}$$

$$\int_0^{V_1} dV = C \int_0^{t_1} dt \quad \Rightarrow \frac{V_1}{t_1} = C$$

OR

$$\frac{V_1}{t_1} = \frac{A^2(-\Delta P)}{vr\mu(V_1 + \frac{LA}{v})} \tag{22}$$

OR

$$\frac{t_1}{V_1} = \frac{vr\mu}{A^2(-\Delta P)}(V_1 + \frac{LA}{v}) = \frac{vr\mu}{A^2(-\Delta P)}V_1 + \frac{r\mu L}{A(-\Delta P)} \tag{23}$$

OR

$$V_1^2 + \frac{LA}{v}V_1 = \frac{A^2(-\Delta P)}{vr\mu}t_1 \tag{24}$$

For constant pressure filtration

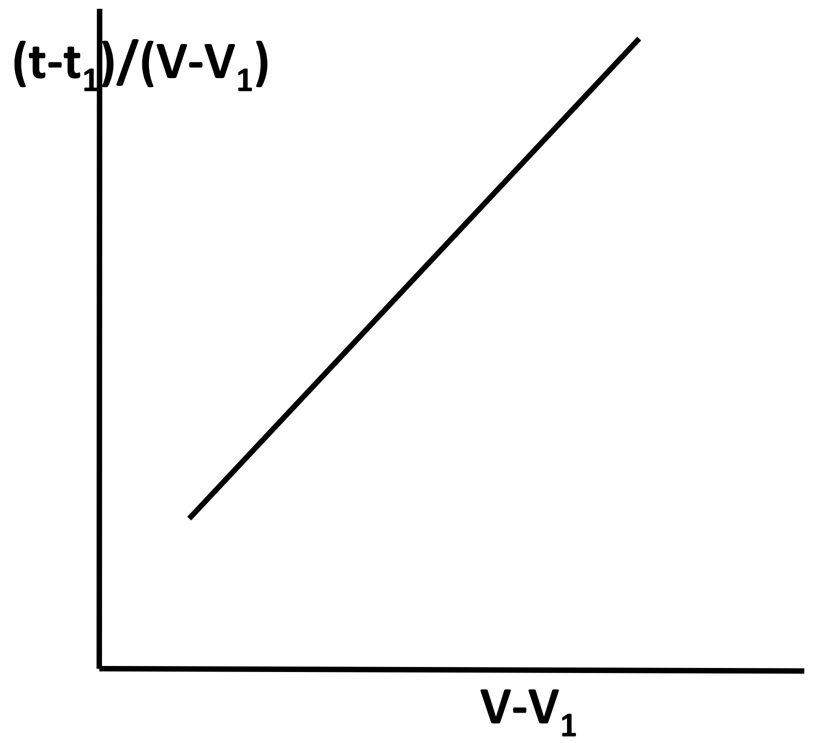
Integration between $t = t_1$, $V = V_1$ and $t = t$, $V = V$

$$\frac{1}{2}(V^2 - V_1^2) + \frac{LA}{v}(V - V_1) = \frac{A^2(-\Delta P)}{r\mu v}(t - t_1) \qquad (25)$$

OR

$$\frac{t - t_1}{V - V_1} = \frac{r\mu v}{2A^2(-\Delta P)}(V - V_1) + \frac{r\mu v}{A^2(-\Delta P)}V_1 + \frac{r\mu L}{A(-\Delta P)} \qquad (26)$$

Plot $(t-t_1)/(V-V_1)$ against $(V-V_1)$



<u>**Note :**</u>

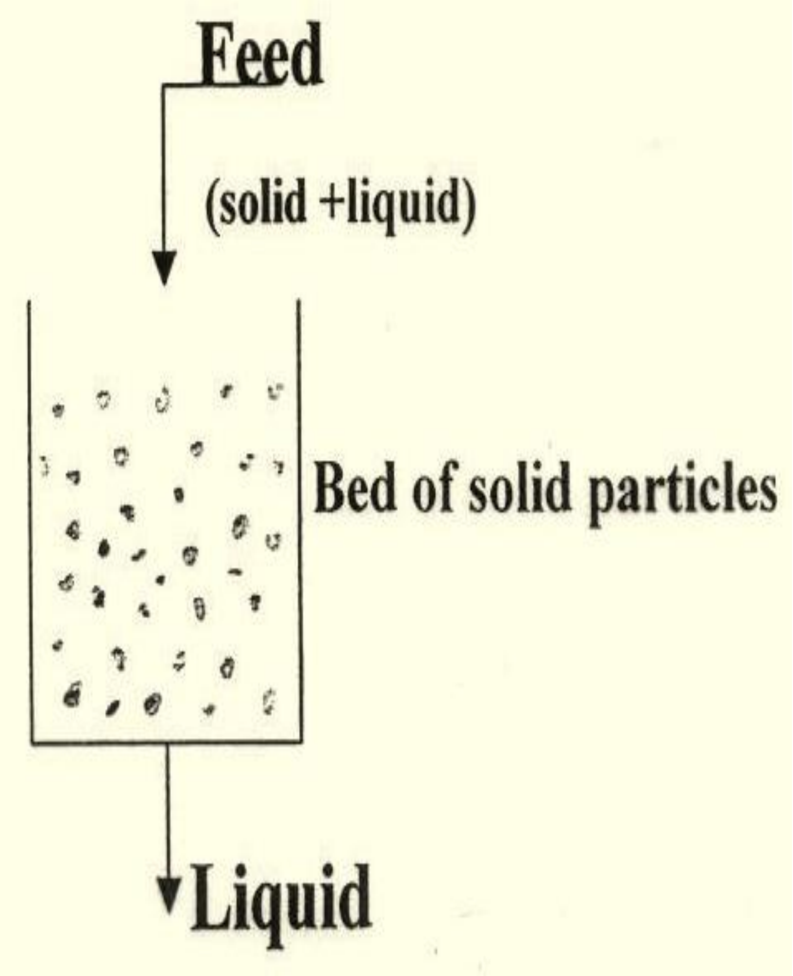
Slope gives sp. resistance r

Intercept yields L the equivalent thickness of cake

Filter types

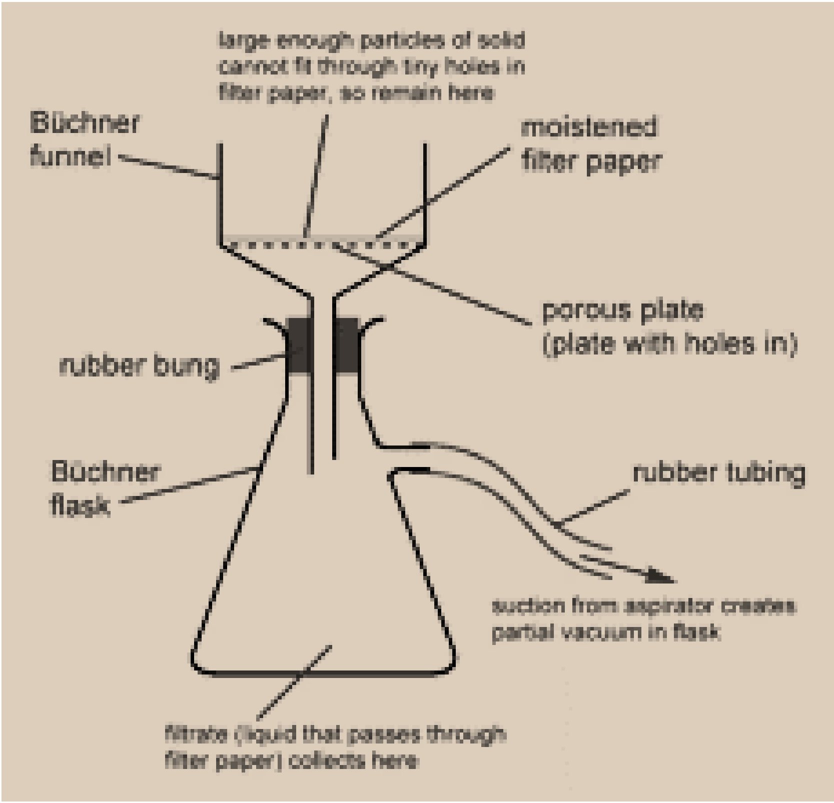
- **Laboratory test filter**

- **Bed filters**



Laboratory test filter

- Filter flask (suction flask, with sintered glass filter containing sample).



Bed filters

***Applications*:** Granular bed filters, Sand filters

Purification of water; Waste water Treatment ~ Solid content:10g/m^3 or less

***Specifications of bed*:** granular solids 0.6-1.2mm size, depth: 0.6-1.8m {not always}

The very fine particles of solids are removed by mechanical action although the particles finally adhere as a result of surface electric forces or adsorption.

Sand filter

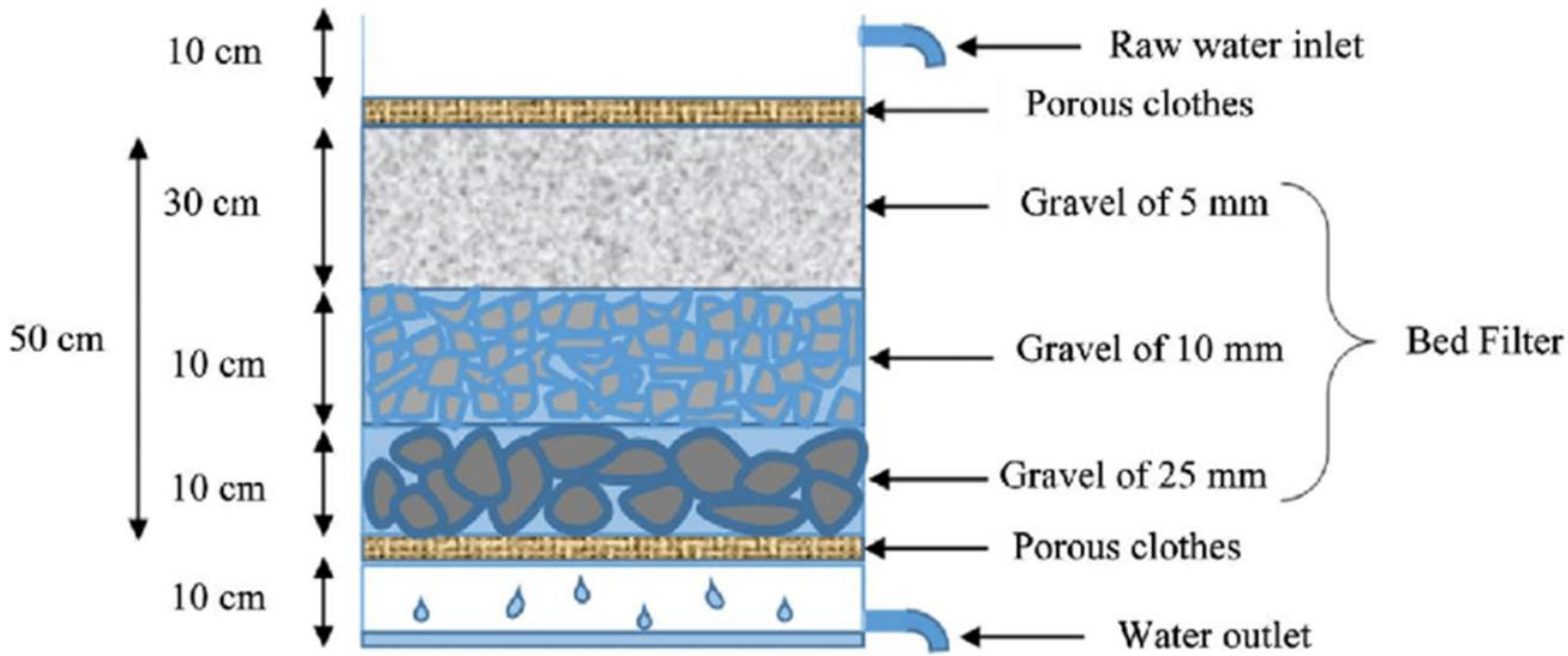
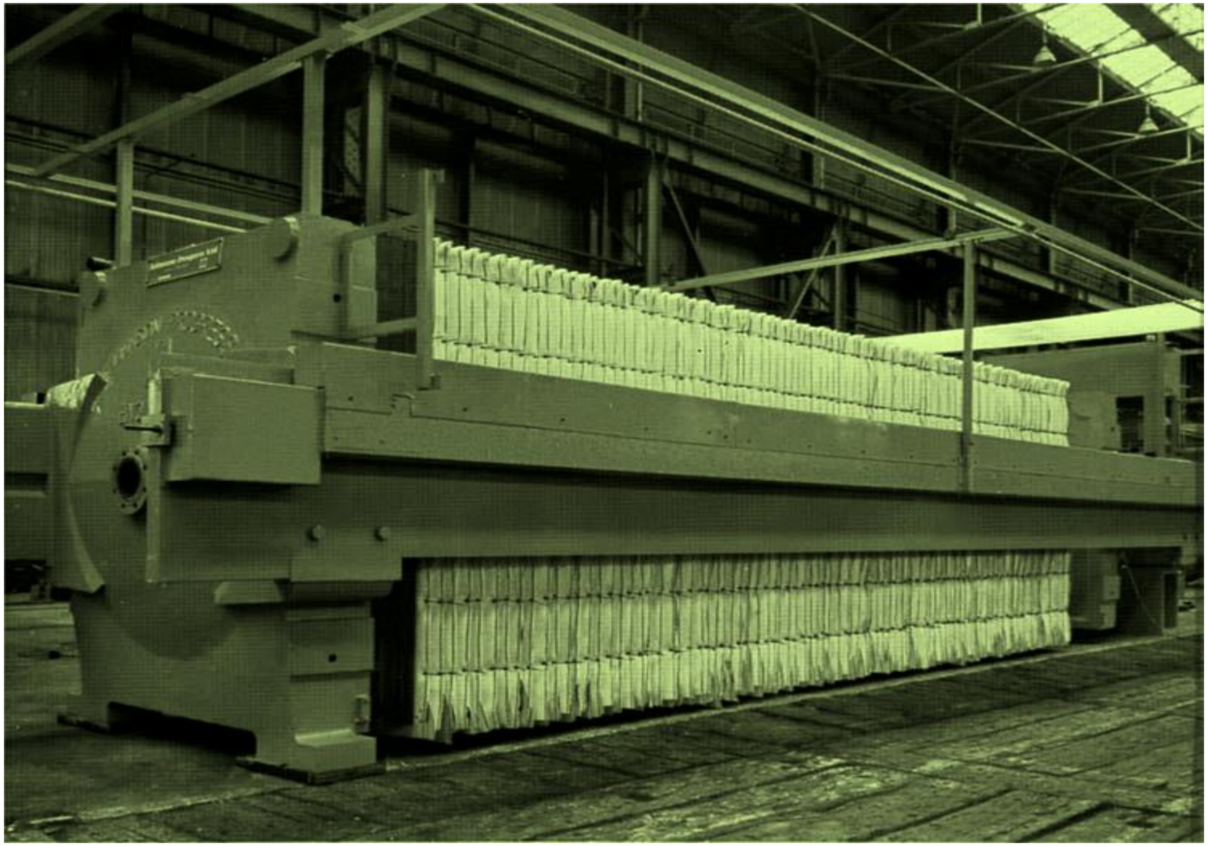

10 cm
Raw water inlet
Porous clothes
30 cm
Gravel of 5 mm
50 cm
10 cm
Gravel of 10 mm
Bed Filter
10 cm
Gravel of 25 mm
Porous clothes
10 cm
Water outlet

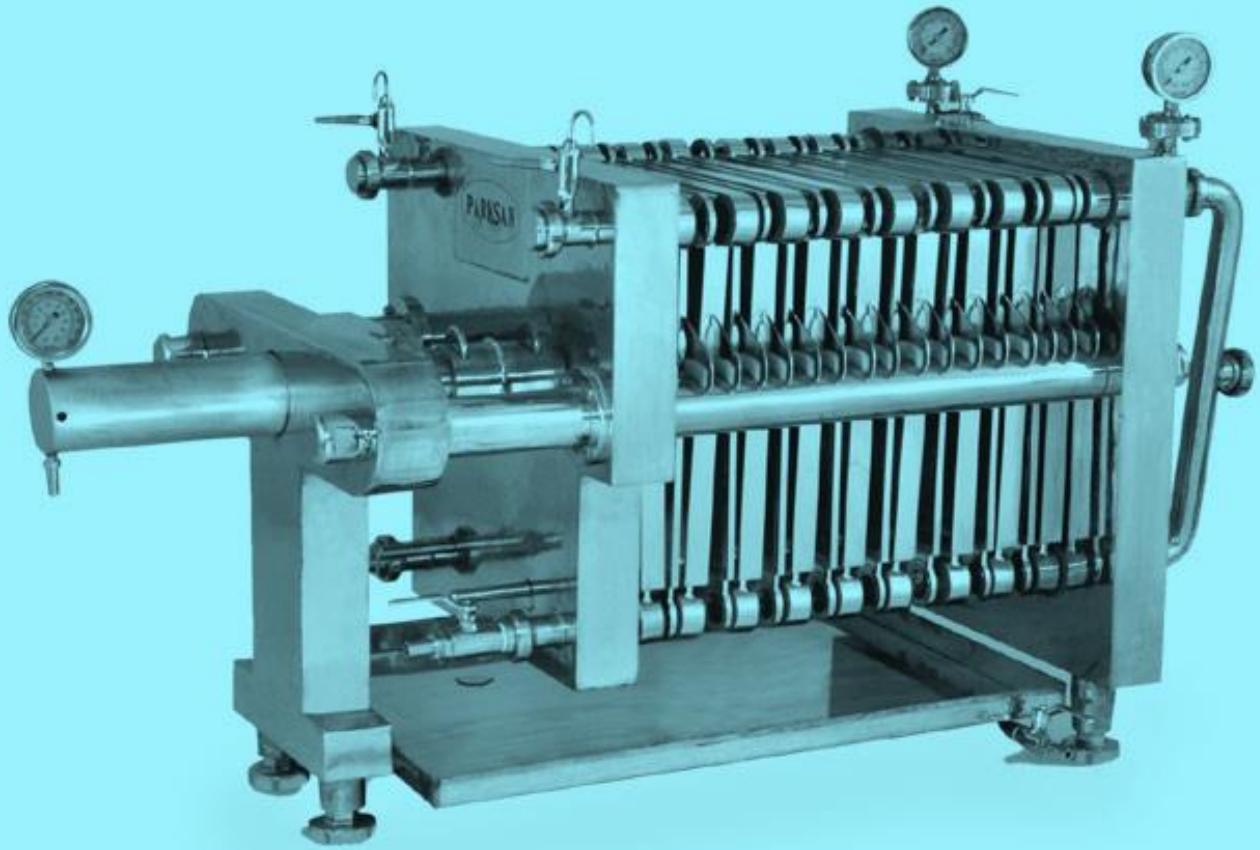
Plate and frame filter press

Here the plates, frames and cloths are pressed together as shown, and the entering slurry passes through lines leading to the frames.



SEPRA

Plate and Frame Type Filter Press



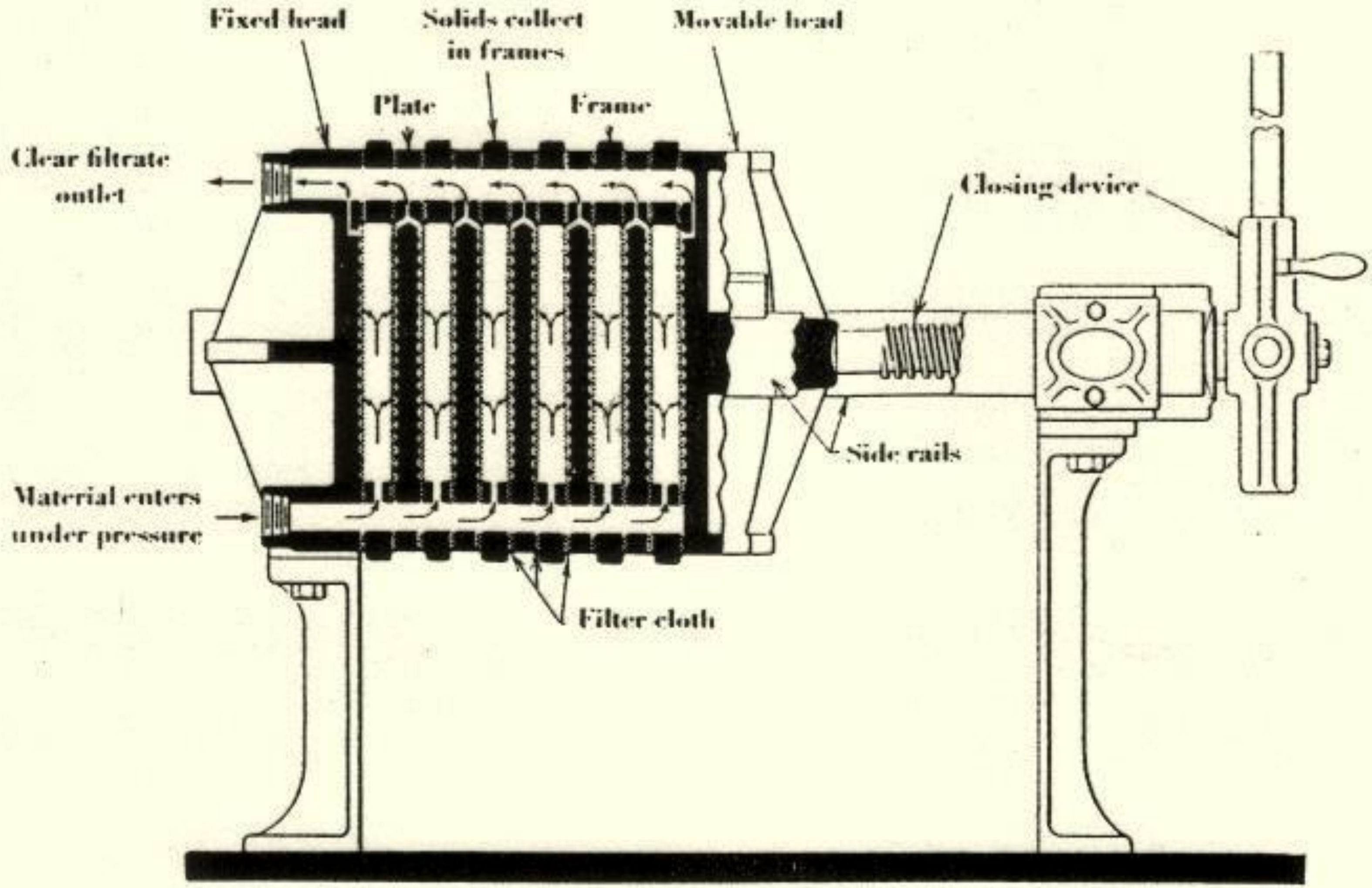
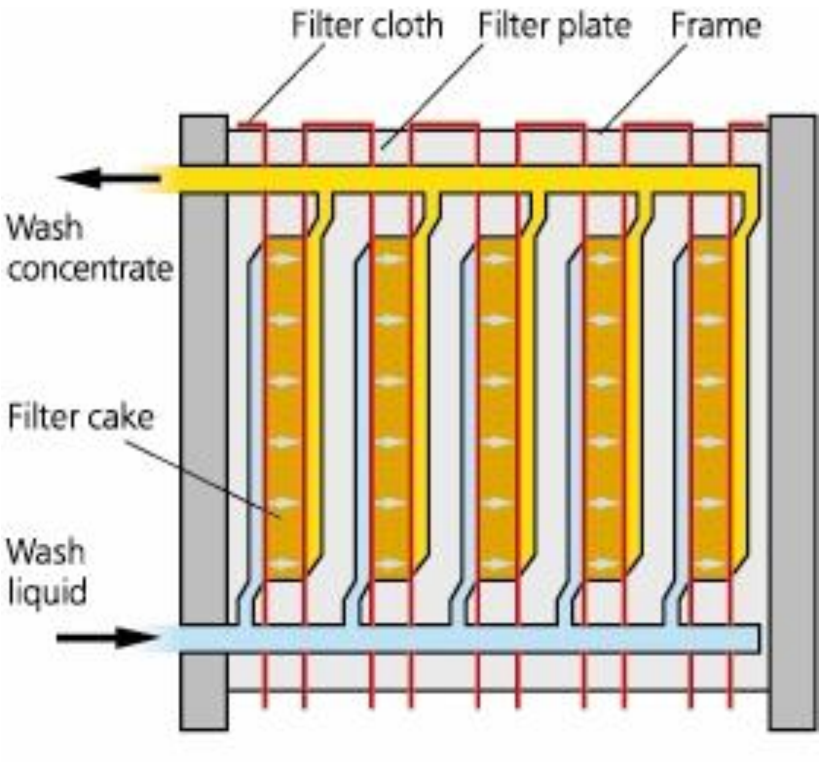
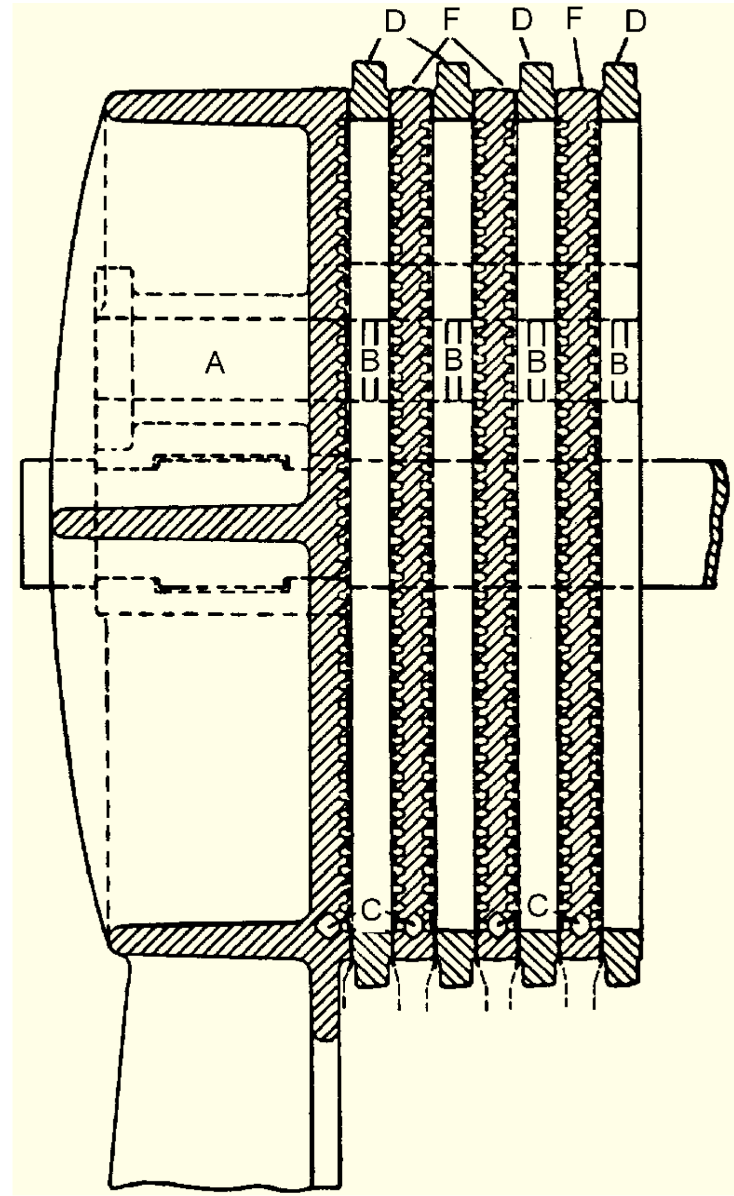
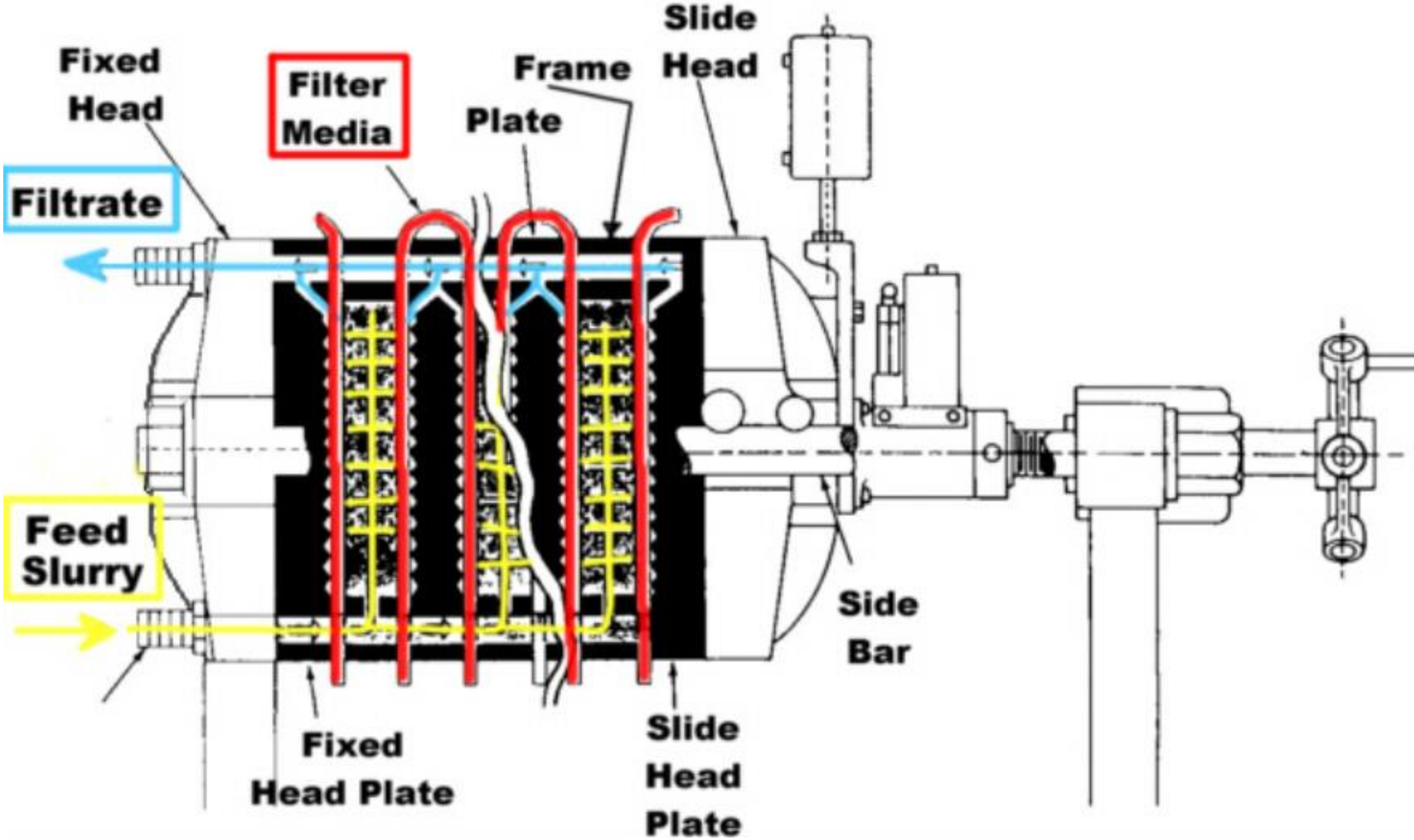

Fixed head
Solids collect in frames
Movable head
Plate
Frame
Clear filtrate outlet
Closing device
Side rails
Material enters under pressure
Filter cloth

Plate and frame press. A–inlet passage. B–feed ports. C–filtrate outlet. D–frames. F–plates



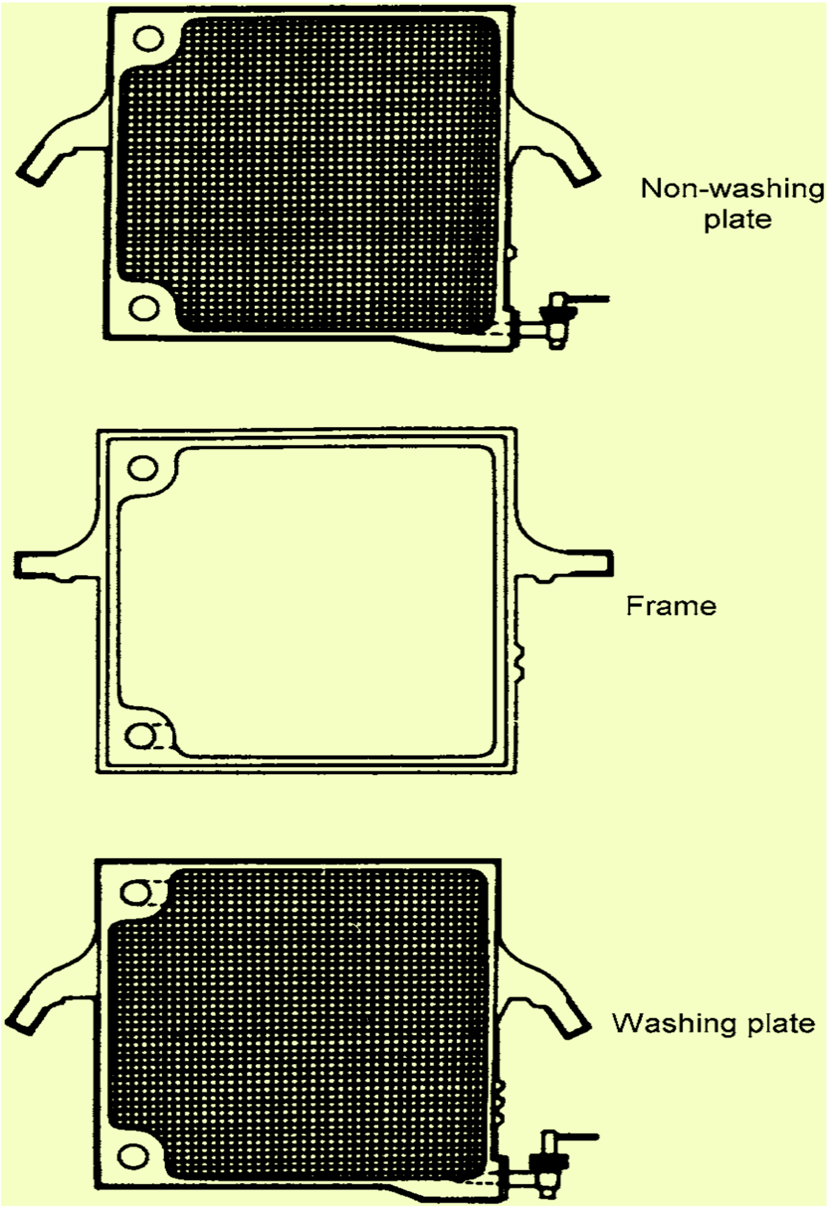
Filter cake washing in a plate and frame filter press



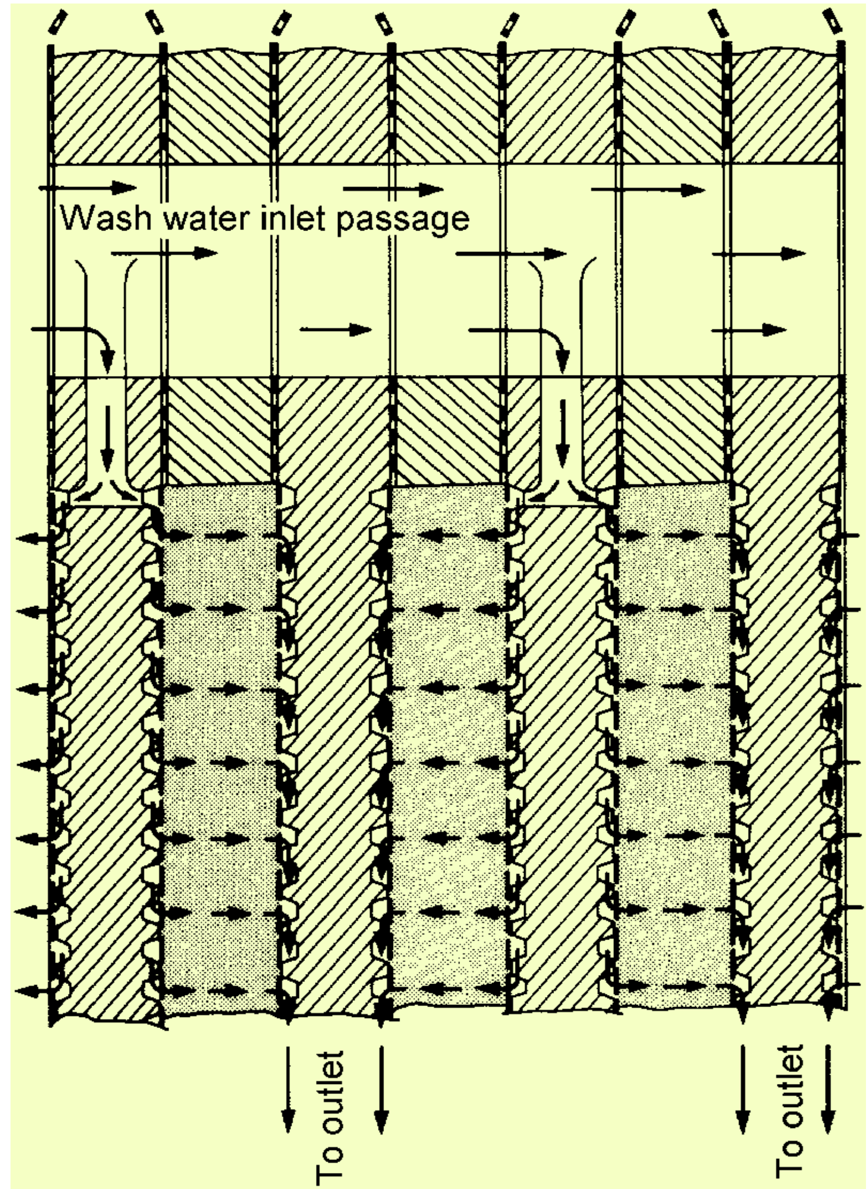


Fixed Head
Filter Media
Frame
Plate
Slide Head
Filtrate
Feed Slurry
Side Bar
Fixed Head Plate
Slide Head Plate

Plates and frames



Thorough washing



- **The cake is deposited against the filter cloths, which form the faces of the frames. The filtrate flows through the grooved channel on the faces of the plates and out through the openings at the tops of the plates.**
- **When the frames are filled with cake, washing can be done by introducing the washing liquid through washing plates. It flows through the entire cake thickness. The press is then opened, the solid removed, and another cycle of filtration started.**

Notes

This type of equipment suffers from the following disadvantages:

- **Process ~ batch**
- **Cost of labor ~ high.**
- **Capacity ~ Low.**
- **Sometimes it requires large quantity of washing liquid.**

Advantages of the filter press

(a) Because of its basic simplicity the filter press is versatile and may be used for a wide range of materials under varying operating conditions of cake thickness and pressure.

(b) Maintenance cost is low.

(c) It provides a large filtering area on a small floor space and few additional associated units are needed.

(d) Most joints are external and leakage is easily detected.

Advantages of the filter press

(e) High pressure operation is usually possible.

(f) It is equally suitable whether the cake or the liquid is the main product.

Optimum time cycle

- *The optimum thickness of cake to be formed in a filter press* **depends on** the resistance offered by the filter cake and **on** the time taken to dismantle and refit the press.

- Although the production of a thin filter cake results in a high average rate of filtration, it is **necessary to dismantle** the press more often and a **greater time** is therefore spent on this operation.
- For a filtration carried out entirely at constant pressure, a rearrangement equation 7.26 gives:

$$\frac{t}{V} = \frac{r\mu v}{2A^2(-\Delta P)}V + \frac{r\mu L}{A(-\Delta P)} \qquad (27)$$

$$= B_1 V + B_2 \qquad (28)$$

where B_1 *and* B_2 *are constants.*

Thus the time of filtration *t is given by:*

$$t = B_1 V^2 + B_2 V \qquad (10)$$

- The time of dismantling and assembling the press, say *t′*, is substantially independent of the thickness of cake produced. The total time of a cycle in which a volume *V of filtrate* is collected is then $(t + t')$ and the overall rate of filtration, W, is given by:

$$W = V/(t + t')$$

$$W = V / (B_1 V^2 + B_2 V + t') \qquad (11)$$

W is a maximum when dW/dV = 0.

Differentiating *W with respect to V and equating to zero:*

$$B_1 V^2 + B_2 V + t' - V(2B_1 V + B_2) = 0$$

$$\therefore \; t' = B_1 V^2 \qquad (12)$$

$$\text{Or} \quad V = \sqrt{\frac{t'}{B_1}} \qquad (13)$$

Notes

- If the resistance of the filter medium is neglected, $t = B_1V^2$ *and the time during which* filtration is carried out is exactly equal to the time the press is out of service.
- In practice, in order to obtain the maximum overall rate of filtration, the filtration time must always be somewhat greater in order to allow for the resistance of the cloth, represented by the term B_2V.
- *In general, the lower the specific resistance of the cake, the greater will be the* economic thickness of the frame.

Washing Process

Washing Stages

- Displacement washing (90% removal of filtrate)
- Diffusion washing (washing material diffuses in the pores of the cake)

Drying Process

Air is used to dry the filter cake.

Note

The rate of washing is usually taken at the same pressure difference and the same final rate of filtration.

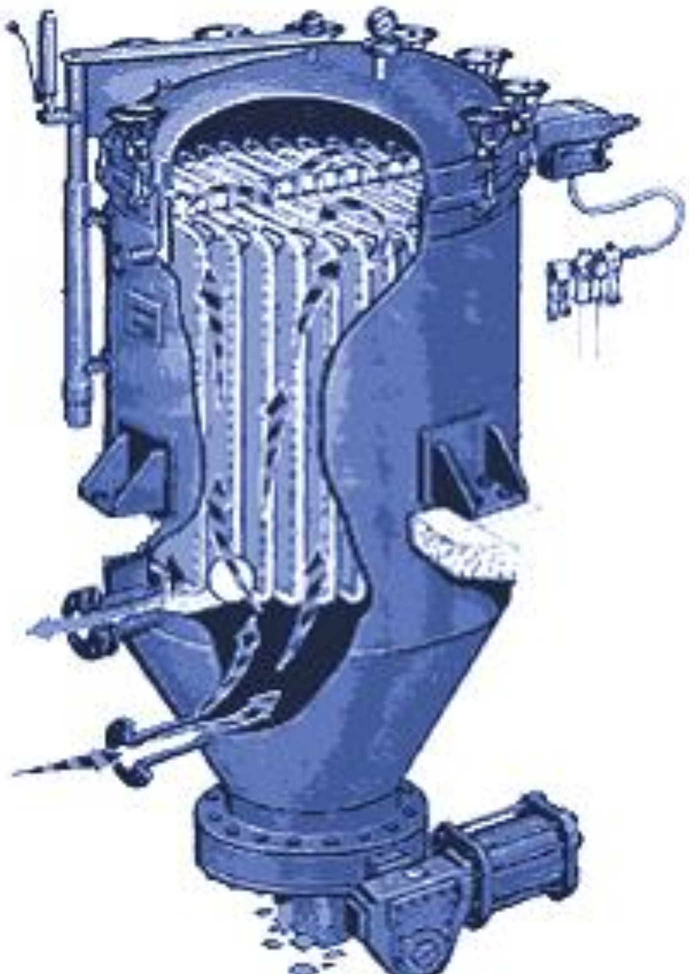
Methods of washing

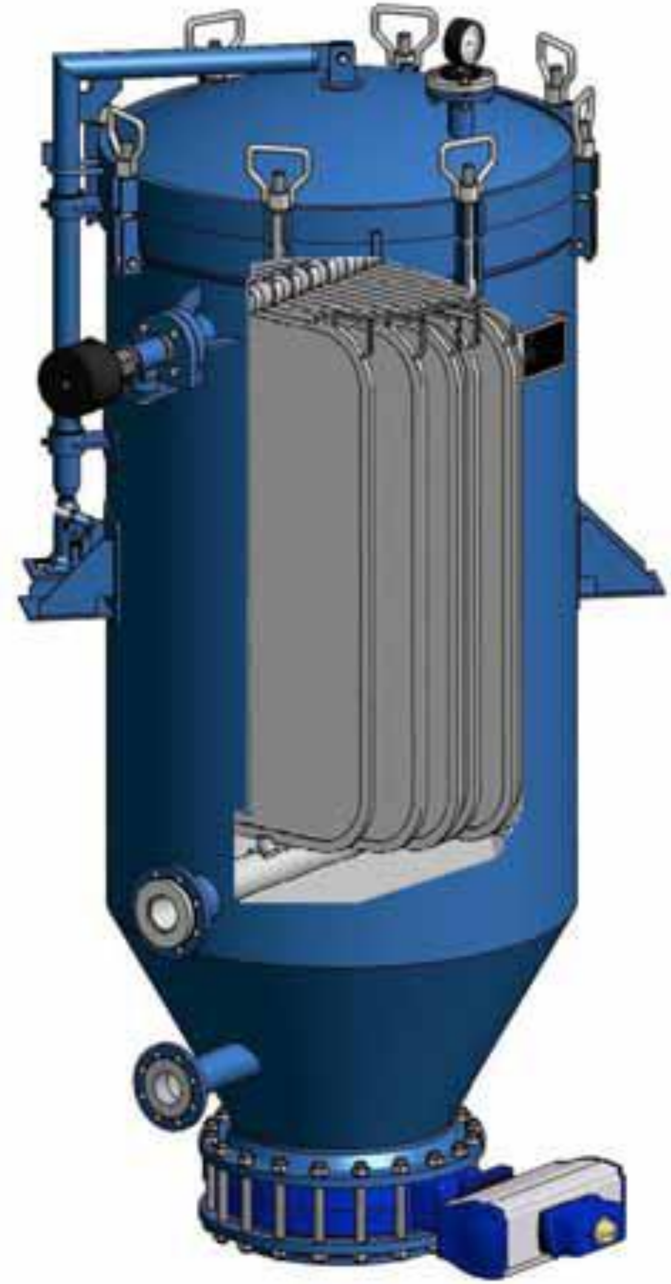
1) Simple washing : ‘the washing liquid passes through the same passage of slurry’.
2) Thorough washing : ‘washing liquid introduces through a specific plates called washing plates’. In general, the liquid passes through the whole thickness of the cake. Therefore, the area during washing is ½ the area during the filtration and the wash liquid flows through twice the thickness of cake so the washing rate is about ¼ of the final rate of the filtration. “***<u>See slide 41 and examples</u>***”

Leaf Filter

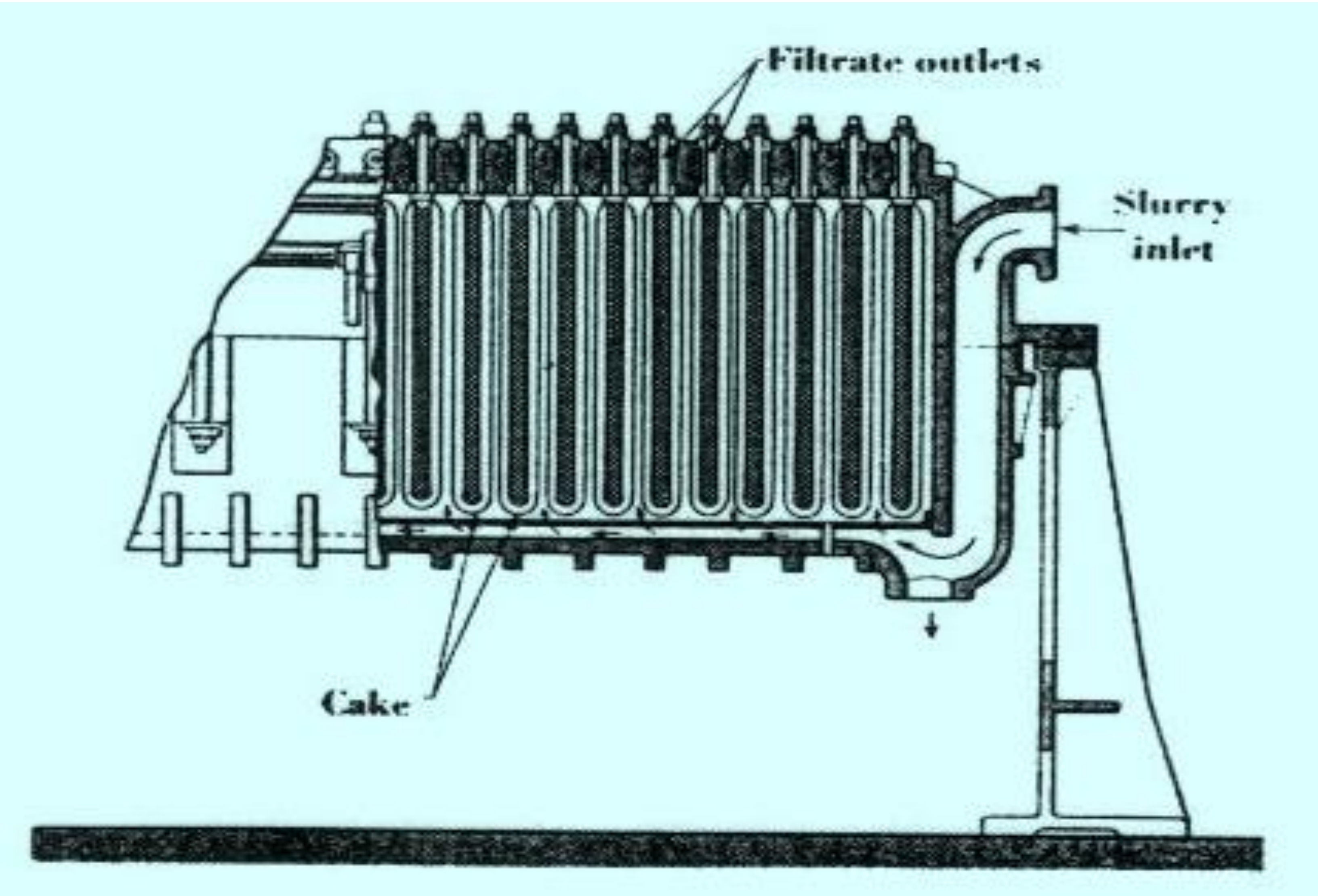
- This filter was developed for large volume of slurry and more efficient washing.
- Each leaf is a hollow wire framework covered by a sack (bag) of filter cloth.
- Shape: rectangular leaves
- ***Arranged longitudinally in side a cylindrical shell.***
- **The feed is pumped under pressure (>150psi) into a shell (it can be maintained by using a compressed air).**

Leaf filter

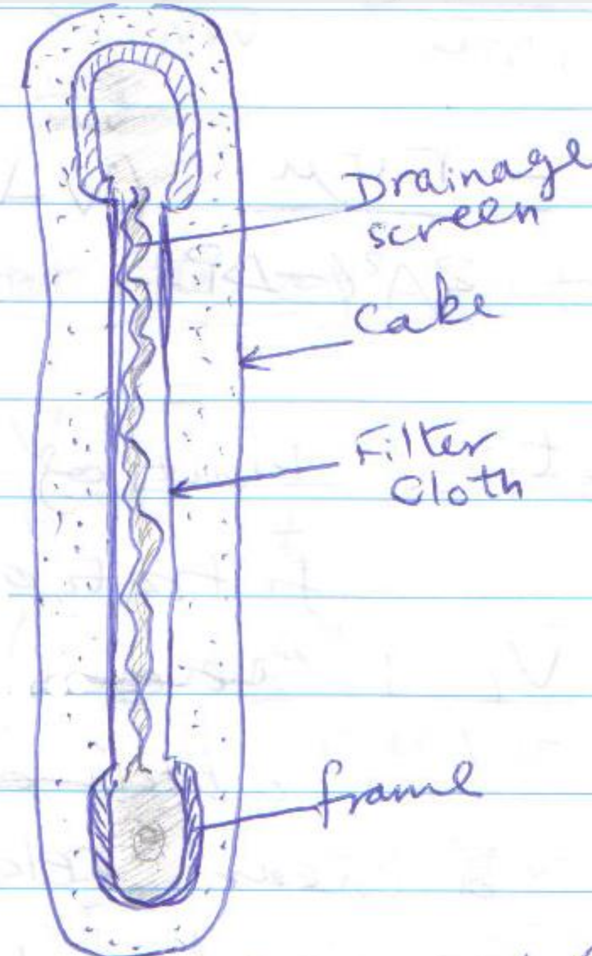




Leaf Filter



leaf Filters < vacuum operation eg Moore filter / pressure operation eg Kelly filter



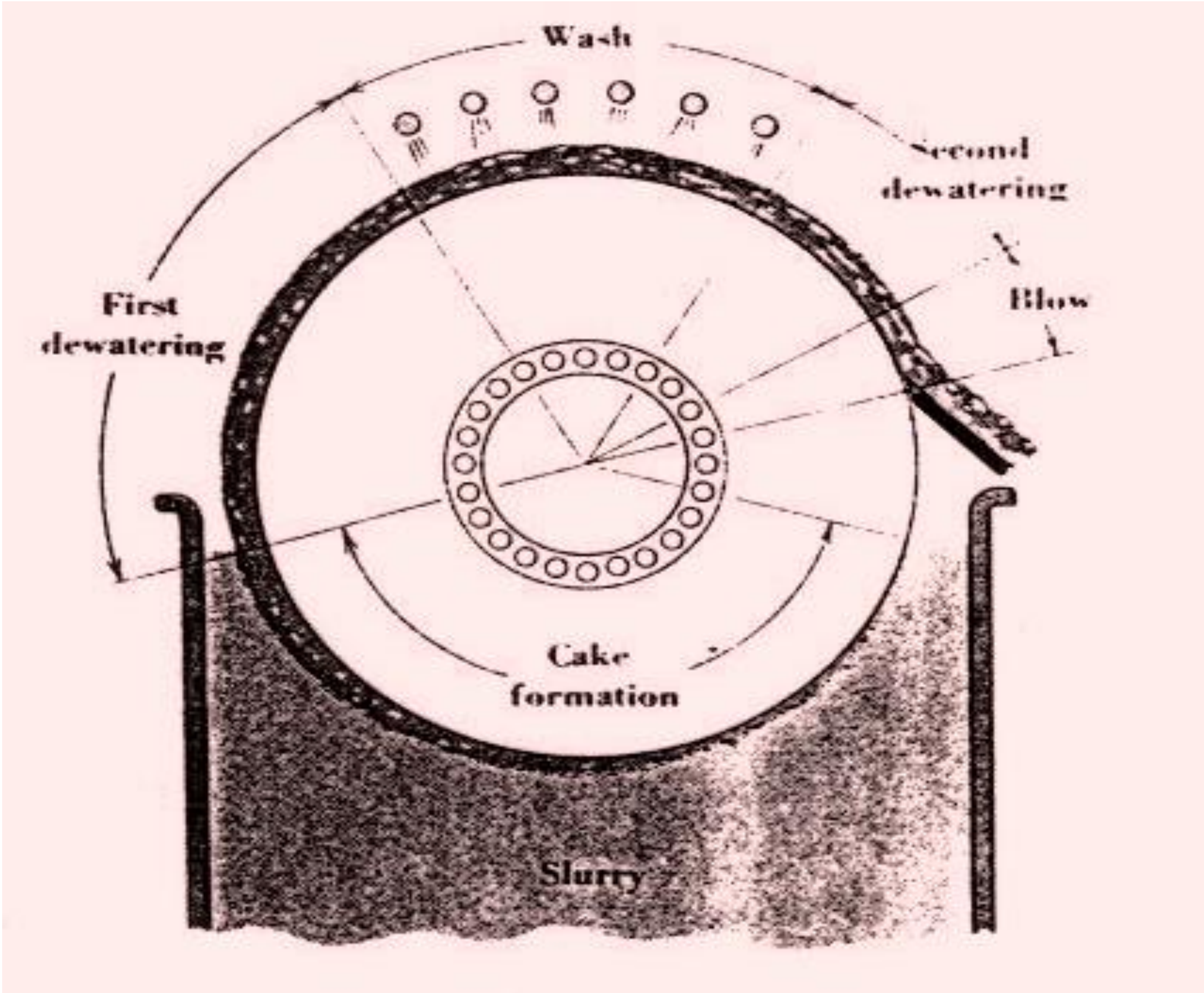
Filter leaf from a Kelly filter

Leaf Filter

- The filtrate is removed from inside of the leaves and the cake forms on the outside.
- **The wash liquid follows the same path as the slurry.**
- When sufficient cake is deposited, the shell is opened and the cake removed.
- The filter suffers from the disadvantages common to batch operations.

A continuous rotary filter

- **The advantages of continuous operation are achieved by the use of a rotary vacuum filter of the type shown in the following figure.**



Wash
Second
dewatering
Blow
First
dewatering
Cake
formation
Slurry

- **A vacuum is maintained on the interior of the rotating drum, which is covered on its curved surface by the filter medium.**
- **The drum dips into a tank of slurry, and the filtrate passes through the medium and removed through the axle of the filter.**
- **The cake is continuously washed and removed using a knife scraper.**

- **The max. pressure differential for the vacuum filter is only 1 atm. Therefore, this type is not suitable for viscous liquids or for liquids which cannot be exposed to the atmosphere. These problems can be overcome by enclosing the filter in a shell, which is maintained above atmospheric pressure.**