FILTRATION AND SEDIMENTATION

CONCEPT OF FILTRATION

- *The separation of solids from a suspension in a liquid with the help of a porous medium or screen which retains the solids and allows the liquid to pass* is termed as **filtration**.
- The operation of separating a solid from a liquid by means of a porous medium (usually a wire or fabric filter cloth) is called as filtration. The medium retains the solid in the form of a porous cake, while the liquid passes through it.
- The mechanical separation of a solid from suspension in a liquid by passage through a porous medium which retains the solid and allows the liquid to pass is called as filtration.
- In filtration operation, the volume of the suspensions to be handled may vary from extremely large quantities (as in water purification) to relatively small quantities (as in the fine chemical industry), the suspensions may contain small or large proportions of solids and the valuable product may be the solid, the liquid, or both or sometimes none of them (e.g., the waste solids to be separated from a waste liquid prior to the disposal). The driving force required for a separation by filtration based upon the nature of a suspension may be divided into four categories, namely gravity, vacuum, pressure and centrifugal.
- Separation of suspended impurities from water (in water purification), separation of solid organic and inorganic materials from their slurry such as calcium carbonate, ammonium sulphate, sugar, paranitroaniline, etc. are some examples of filtration.

Types of Filtration : Cake Filtration and Deep Bed Filtration

- Basically, there are two types of filtration.

  (i) Cake filtration, (ii) Deep bed filtration.
- In cake filtration, the proportion of solids in the suspension is large and most of the solid particles are collected in the cake which can later be detached from the filter medium.
- In deep bed filtration, the proportion of solids is very small and the particles of the solid being smaller than the pores of the filter medium will penetrate a considerable depth and ultimately get trapped inside the filter medium and usually no layer of solids will appear on the surface of the medium (e.g., water filtration).

- Thus, filters are divided into two main groups, **clarifying filters** and **cake filters.** Clarifying filters also called as deep bed filters are used to remove small amounts of solids to produce sparkling clear liquids, whereas cake filters separate large amounts of solids in the form of a cake of crystals. Clarifying filters find applications in water treatment. In this chapter, we will deal with cake filtration.

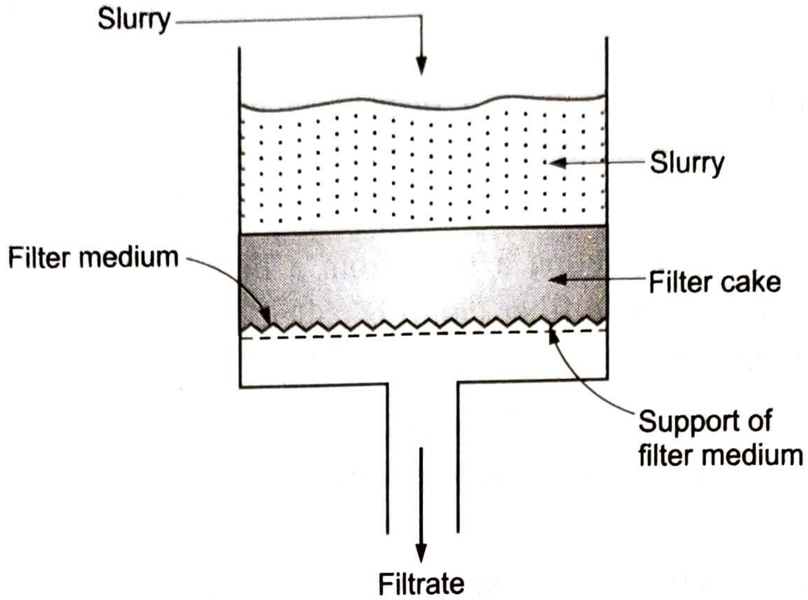

Fig. 5.1 : Principle of filtration

Principles of Cake Filtration :

- In cake filtration, the feed to be handled (two phase mixture) is called **slurry**, the bed of deposited solids on a porous membrane (filter medium) is called **cake** and the clear liquid leaving the filter medium is called **filtrate.**
- A typical cake filtration operation is shown in Fig. 5.1. During the initial period of flow, solid particles are trapped within the pores of a medium forming a true filter medium. The liquid passes through the bed of the solids and through the filter medium. In the early stage of filtration, the rate of filtration is high. As the cake thickness increases, the rate of filtration decreases for a given pressure differential across the filter medium. This is due to the fact that as the cake gradually builds upon the medium, the resistance to flow progressively increases.

Constant Rate and Constant Pressure Filtration

Types of filtration (based on the pressure drop across a filtering medium) :

There are two types of filtration :

1. Constant pressure filtration
2. Constant rate filtration.

- *The method in which the pressure drop over the filter is held constant throughout a run so that the rate of filtration is maximum at the start of filtration and decreases continuously towards the end of the run* is called **constant pressure filtration.** If the outlet pressure is constant, constant pressure filtration is carried out by applying a certain pressure at inlet and maintaining it constant throughout the run.

- *The method in which the pressure drop is varied usually from a minimum at the start of filtration to a maximum at the end of filtration so that the rate of filtration is constant throughout the run* is called **constant rate filtration.**
- In constant rate filtration, nearly constant rate of filtration is maintained by starting at low inlet pressure, and continuously increasing the pressure to overcome the resistance of cake, until the maximum pressure is reached towards the end of the run.
- In constant pressure filtration, application of high initial pressure results in a low rate of filtration as the first particles filtered will be compacted into a tight mass that largely fills the pores of cloth. In constant rate filtration, as the maximum pressure is reached towards the end of the run whole cycle is operated at less than the maximum capacity. To overcome the difficulties faced in the filtration types cited above, a practical solution is found out by carrying out the filtration at constant rate until the inlet pressure reaches a specified maximum and then to continue at constant pressure until the end of the run.

Distribution of overall pressure drop

- With the help of the pressure difference applied between the slurry inlet and the filtrate outlet, the filtrate is forced through a filter. During filtration, the solids are retained in the form of cake through which the filtrate must flow. The filtrate has to pass through three resistances in series –
  1. Resistance of the feed and filtrate channel,
  2. Resistance of the cake, and
  3. Resistance offered by the filter medium.
- The overall or total pressure drop over the filter at any time is equal to the sum of the individual pressure drops over the medium and cake. Usually, the resistances offered by the inlet and outlet connections are small as compared with those offered by the cake and medium and thus, can be neglected.

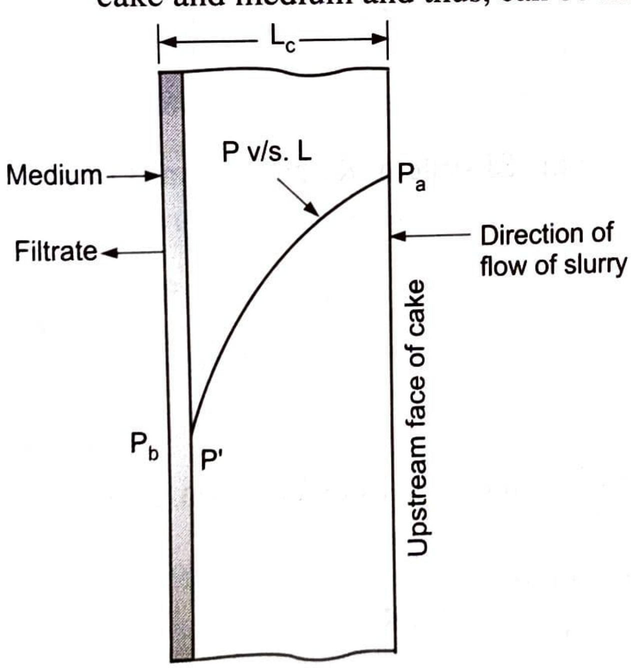

Fig. 5.2 : Section through filter medium cake showing pressure drop

- By the resistance of filter medium or filter medium resistance, we mean it is the entire resistance built up in the filter medium, including that from the trapped particles. Filter medium resistance is important in the early stages of filtration. The cake resistance is the one which is offered by all solids not associated with the filter medium. It is zero at the start of filtration and goes on increasing with time of filtration.

- If the resistance of the inlet and outlet channels is neglected then the overall pressure drop is the sum of pressure drops over the medium and cake.

$$\Delta P = P_a - P_b = (P_a - P') + (P' - P_b) = \Delta P_c + \Delta P_m \qquad \ldots (5.1)$$

where
P_a = inlet pressure
P_b = outlet pressure
P' = pressure at the interface between cake and medium
ΔP = overall pressure drop
ΔP_c = pressure drop over cake
ΔP_m = pressure drop over medium

Specific cake resistance :

- A specific cake resistance α can be defined by the equation

$$\alpha = \frac{\Delta P_c A}{\mu u m_c} \qquad \ldots (5.2)$$

where ΔP_c is the pressure drop over the cake, A is the filter area measured perpendicular to the direction of flow, u is the linear velocity of the filtrate based on the filter area, μ is the viscosity of the filtrate, and m_c is the total mass of solids in the cake. In the SI system, the units of α are m/kg and has dimensions of $M^{-1} L^{1}$.

[ΔP_c in N/m², A in m², μ in (N.s)/m² and u in m/s]

Filter medium resistance :

A filter medium resistance can be defined by the equation

$$\frac{\Delta P_m}{R_m} = \mu u \qquad \ldots (5.3)$$

$$\therefore \quad R_m = \Delta P_m / \mu u \qquad \ldots (5.4)$$

where ΔP_m is the pressure drop over filter medium. In the SI system, R_m has the units of m^{-1}. The dimension of R_m is L^{-1}.

Rearranging Equation (5.2), we get

$$\Delta P_c = \mu u m_c \alpha / A \qquad \ldots (5.5)$$

Rearranging Equation (5.4), we get

$$\Delta P_m = \mu u R_m \qquad \ldots (5.6)$$

Substituting the values of ΔP_c from Equation (5.5) and ΔP_m from Equation (5.6) into Equation (5.1), we get

$$\Delta P = \Delta P_c + \Delta P_m = \frac{\mu u m_c \alpha}{A} + \mu u R_m$$

$$\therefore \quad \Delta P = \mu u \left[\frac{m_c \alpha}{A} + R\right] \qquad \ldots (5.7)$$

- In using Equation (5.7), it is convenient to replace u, the linear velocity of the filtrate, and m_c, the total mass of the solid in the cake, by functions of V, the total volume of filtrate collected in time t.
- If c is the mass of particles deposited in the filter per unit volume of filtrate, then the mass of solids in the filter at time t is given by

$$m_c = cV \qquad \text{... (5.8)}$$

- The linear velocity of the filtrate is given by the equation

$$u = \frac{dV/dt}{A} \qquad \text{... (5.9)}$$

where V is the volume of filtrate collected from the start of filtration to time t and A is the filter area normal to the direction of flow of filtrate.

- Substituting u from Equation (5.9) and m_c from Equation (5.8) in Equation (5.7), we get

$$\Delta P = \mu \frac{dV/dt}{A}\left[\frac{c\,V\,\alpha}{A} + R_m\right]$$

$$\frac{dt}{dV} = \frac{\mu}{A\,\Delta P}\left[\frac{c\,\alpha\,V}{A} + R_m\right] \qquad \text{... (5.10)}$$

or

$$\frac{dV}{A\,dt} = \frac{\Delta P}{\mu\left[\frac{c\,V\,\alpha}{A} + R_m\right]} \qquad \text{... (5.11)}$$

- Equation (5.11) expresses the differential or instantaneous rate of filtration per unit area of the filtering surface as the ratio of the pressure drop (driving force) to the product of the viscosity of the filtrate and the sum of the cake resistance and the filter medium resistance.

Constant Pressure filtration

When ΔP is constant, V and t are the only variables in Equation (5.10).

When t = 0, V = 0, and $\Delta P = \Delta P_m$. Therefore, Equation (5.10) becomes

$$\frac{\mu R_m}{A\,\Delta P} = \left(\frac{dt}{dV}\right)_0 = \frac{1}{q_0} \qquad \text{... (5.12)}$$

Thus, Equation (5.10) may also be rewritten as

$$\frac{dt}{dV} = \frac{1}{q} = K_c V + \frac{1}{q_0} \qquad \text{... (5.13)}$$

$$\frac{dt}{dV} = \frac{\mu \alpha c V}{A^2 \Delta P} + \frac{\mu R_m}{A \Delta P}$$

$$\frac{dt}{dV} = K_c V + \frac{1}{q_o} \qquad \dots (5.14)$$

where $$K_c = \frac{\mu \alpha c}{A^2 \Delta P} \qquad \dots (5.15)$$

Integrating Equation (5.14) between the limits : t = 0, V = 0, and t = t, V = V

$$\int_0^t dt = \int_0^V \left(K_c V + \frac{1}{q_o}\right) dV$$

$$t = \frac{K_c V^2}{2} + \frac{V}{q_o} \qquad \dots (5.16)$$

Substituting values of K_c and $1/q_o$ from Equations (5.15) and (5.12) in Equation (5.16), we get

$$t = \frac{\mu \alpha c}{2 A^2 \Delta P} V^2 + \frac{\mu R_m V}{A \Delta P}$$

$$t = \frac{\mu}{\Delta P}\left[\frac{c \alpha}{2}\left(\frac{V}{A}\right)^2 + R_m\left(\frac{V}{A}\right)\right] \qquad \dots (5.17)$$

Rearranging Equation (5.16), we get

$$\frac{t}{V} = \frac{K_c}{2} V + \frac{1}{q_o} \qquad \dots (5.18)$$

Hence, a plot of t/V v/s V is a straight line with a slope equal to $K_c / 2$ and an intercept equal to $1/q_o$. From this plot and Equations (5.12) and (5.15), the values of α and R_m can be calculated.

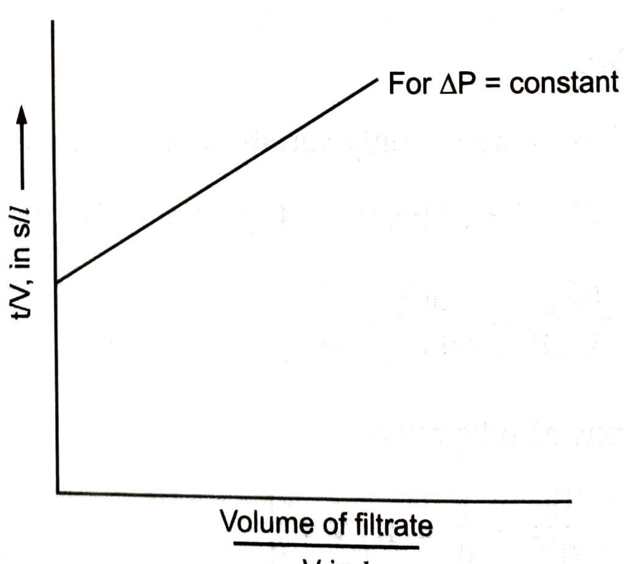

Fig. 5.3 : Plot of t/V v/s V

Empirical equations for cake resistance

- The variation of α with ΔP can be found out by conducting constant-pressure experiments at various values of ΔP.
- The specific cake resistance can be related to the pressure drop by the following empirical equation

$$\alpha = \alpha_o (\Delta P)^s \qquad \ldots (5.19)$$

where α_o and s are empirical constants. The constant 's' is known as the compressibility coefficient of the cake. It is zero for incompressible sludges [i.e., α is independent of (ΔP) – the sludge is incompressible] and positive for compressible sludges [i.e., α increases with (ΔP) – the sludge is compressible]. For commercial slurries, the value of 's' usually lies between 0.2 and 0.8.

- For obtaining the value of s, we have to plot α as a function of (ΔP) on the logarithmic co-ordinates. The slope of the line obtained gives the value of 's' and intercept gives the value of α_o.
- In Equation (5.17), α is to be replaced by its value given by Equation (5.19) and then is directly applicable for use in the design of batch filters (constant pressure). The constants α_o, s, R_m must be evaluated experimentally, and the general equation can then be applied to conditions of varying A, ΔP, V, t, c and μ.
- If m_F is the mass of the wet cake and m_c is the mass of the dry cake after washing and drying, ρ is the density of the filtrate and c_s is the concentration of solids in the slurry in kg per m³ of the liquid fed to the filter, then the mass of the particles that are deposited in the filter per unit volume of filtrate is given by

$$c = \frac{c_s}{[1 - (m_F / m_c - 1)]\, c_s / \rho} \qquad \ldots (5.20)$$

where ρ in kg/m³, c_s is in kg/m³.

Constant-rate filtration :

- When filtrate flows at a constant rate, the linear velocity u is constant

$$\therefore \quad u = \frac{dV/dt}{A} = \frac{V}{A\,t} \qquad \ldots (5.21)$$

We have :

$$\alpha = \frac{\Delta P_c\, A}{\mu\, u\, m_c} \qquad \ldots (5.22)$$

and

$$m_c = cV \qquad \ldots (5.23)$$

- Substituting u from Equation (5.21) and m_c from Equation (5.23) into Equation (5.22) and rearranging, we get

$$\frac{\Delta P_c}{\alpha} = \frac{\mu c}{t} \left(\frac{V}{A}\right)^2 \qquad \ldots (5.24)$$

- If α is known as a function of ΔP_c, and if ΔP_m is estimated, then Equation (5.24) can be used for relating the overall pressure drop to time when the rate of filtration is constant. Equation (5.24) can be used directly if Equation (5.19) is used for relating α with ΔP_c. If α from Equation (5.19) is substituted in Equation (5.24) and if ΔP_c is substituted by $\Delta P - \Delta P_m$, then Equation (5.24) becomes

$$(\Delta P_c)^{1-s} = \alpha_o \, \mu \, c \, t \left(\frac{V}{A\,t}\right)^2 = (\Delta P - \Delta P_m)^{1-s} \quad \dots (5.25)$$

- The simplest method of correcting the overall pressure drop for the pressure drop through the medium is to assume the filter medium resistance to be constant during a constant rate filtration. Then by Equation (5.3), ΔP_m is also constant in Equation (5.25). As the only variables in Equation (5.25) are ΔP and t, Equation (5.25) can be written as

$$(\Delta P - \Delta P_m)^{1-s} = K_r \, t \quad \dots (5.26)$$

where $$K_r = \mu \, u^2 \, c \, \alpha_o \quad \dots (5.27)$$

Continuous Filtration

- In a continuous filter such as rotary drum filter, the feed, filtrate and cake move at steady constant rates. But for any particular element of the filter surface, conditions are unsteady. The process of filtration consists of several steps in series such as cake formation, washing, drying and discharging/scrapping and each of these steps involve gradual and continual change in conditions but the pressure drop across the filter during cake formation is held constant. Therefore, the equations obtained for discontinuous constant-pressure filtration may be applied to continuous filters with some changes.
- Let t be the actual filtering time (the time for which the filter element is immersed in the slurry). With this Equation (5.18) can be rewritten as

$$t = \frac{K_c V^2}{2} + \frac{1}{q_o} \quad \dots (5.28)$$

where V is the volume of filtrate collected in time t.

Equation (5.28) is a a quadratic equation in V which on solving yields

$$V = \frac{(1/q_o^2 + 2\,K_c t)^{1/2} - 1/q_o}{K_c} \quad \dots (5.29)$$

Substituting the values of q_o and K_c, we get

$$V = \frac{[(\mu R_m / A \Delta P)^2 + (2\,\mu\, c\, \alpha / A^2 \Delta P) t]^{1/2} - \mu R_m / A\, \Delta P}{\mu\, c\, \alpha / A^2\, \Delta P}$$

Taking $\mu / A\,\Delta P$ common, we get

$$V = \frac{A\,[R_m^2 + 2\,\Delta P\, c\, \alpha . t/\mu]^{1/2} - R_m}{c\,\alpha}$$

$$\therefore \quad \frac{V}{A} = \frac{[R_m^2 + 2\,\Delta P\, c\, \alpha\, t/\mu]^{1/2} - R_m}{c\,\alpha}$$

Dividing both sides by t, we get

$$\frac{V}{At} = \frac{[(R_m/t)^2 + 2\,\Delta P\, c\, \alpha/\mu\, t]^{1/2} - R_m/t}{c\,\alpha} \quad \text{... (5.30)}$$

where V/t is the rate of filtrate collection and A is the submerged area of the filter.

If $\dot{m}_c$ is the rate of solids production, t_c is the cycle time, A_T is the total filter area, n is the drum speed and f is the fraction of the drum submerged, then

$$t = f\,t_c = f/n \quad \text{... (5.31)}$$

The rate of solids production using Equation (5.8) becomes

$$\dot{m}_c = \frac{m_c}{t} = \frac{cV}{t} = c\left(\frac{V}{t}\right) \quad \text{...(5.32)}$$

As $A/A_T = f$, the rate of solids production divided by the total area of the filter using Equations (5.30), (5.31) and (5.32) thus becomes

$$\frac{\dot{m}_c}{A_T} = \frac{[2c\,\alpha\,\Delta P\, fn/\mu + (n\,R_m)^2]^{1/2} - n\,R_m}{\alpha} \quad \text{... (5.33)}$$

The filter-medium resistance R_m includes the resistance offered by the cake which is not removed by the discharge mechanism provided and carried through the next cycle. If the filter medium is washed after the cake discharge, R_m is usually negligible. Therefore, neglecting R_m, Equation (5.33) becomes

$$\frac{\dot{m}_c}{A_T} = \left(\frac{2c\,\Delta P\, fn}{\alpha\,\mu}\right)^{1/2} \quad \text{... (5.34)}$$

If the specific cake resistance (α) varies with overall pressure drop as per Equation (5.19), then Equation (5.34) becomes

$$\frac{\dot{m}_c}{A_T} = \left(\frac{2\,c\,(\Delta P)^{1-s}\, f\, n}{\alpha_o\,\mu}\right)^{1/2} \quad \text{... (5.35)}$$

- Equations (5.33) and (5.34) are applicable to continuous vacuum filters as well as to continuous pressure filters.
- When R_m is negligible, Equation (5.34) predicts that the rate of filtrate flow varies inversely with the square root of the viscosity and of the cycle time. This is true in practice for thick cakes and long cycle times. But for short cycle times, it is not true and Equation (5.33) must be used.

Filter Medium (Characteristics of filter medium)

- In case of cake filtration, the choice of a filter medium is often the most important consideration in assuring satisfactory operation of a filter. The filter medium in any filter must meet the following requirements :

1. It should retain the solids to be filtered, giving a reasonably clear filtrate.

2. It should not plug or blind (low rate of entrapment of solids within its interstices).
3. It should be mechanically strong to withstand the process conditions.
4. It should be resistant to the corrosive action of fluid.
5. It should offer as little resistance as possible to the flow of filtrate.
6. It should possess ability to discharge cake easily and cleanly.
7. It should have acceptable resistance to mechanical wear.
8. It should be cheap.
9. It should have long life.

- In cake filtration, the filter medium is frequently a textile fabric.
- Canvas cloth, woolen cloth, metal cloth of monel or stainless steel, glass cloth and synthetic fibre cloth - nylon, polypropylene, etc., are commonly used as filter media in industrial filtration practice depending upon the process conditions.
- For an alkaline slurry, nylon cloths are used while for an acidic slurry, polypropylene cloths are used as a filter medium.

Filter Aids

- Filtration of slurries containing very finely divided solids or slimy, deformable flocs is very difficult due to formation of a dense, impermeable cake that quickly plug the filter media. In such cases the porosity of the cake must be increased to allow passage of the filtrate at a reasonable rate. This is achieved by adding a filter aid to the slurry before filtration.
- A filter aid is a granular or fibrous material which packs to form a bed of very high voidage. Because of this, they are capable of increasing the porosity of the filter cake. A filter aid should be of *low bulk density*, should be *porous*, should be *capable of forming a porous cake,* and must be *chemically inert to the filtrate*.
- The commercial filter aids are diatomaceous earth - almost pure silica prepared from deposits of diatom (marine organisms) skeletons, expanded pearlite, and asbestos fibres. The filter aids are used for sludges that are difficult to filter and the use of filter aids is normally restricted to filtration technique in which the filtrate is valuable and the cake is the waste product.
- Methods of using filter aids :

  (i) adding a filter aid to the slurry before filtration, and

  (ii) precoating, i.e., by depositing a layer of a filter aid on the filter medium before filtration.

- Precoats prevent gelatinous solids from plugging the filter medium and give a clear filtrate. The precoat is a part of the medium rather than that of the cake. When the filter aid is directly added to the slurry before filtration, the presence of it increases the porosity of the sludge, decreases its compressibility and reduces the resistance of cake during the filtration operation.

FACTORS AFFECTING RATE OF FILTRATION

The rate at which the filtrate is obtained in a filtration operation, i.e., the rate of filtration depends upon the following factors :

1. Pressure drop across the feed inlet and far side of the filter medium.
2. Area of the filtering surface.
3. Viscosity of the filtrate.
4. Resistance of the filter medium and initial layers of cake.
5. Resistance of the filter cake.

- The rate of filtration is directly proportional to the pressure difference across a filter medium. Therefore, higher the pressure difference across a filter medium, higher will be the rate of filtration.
- The rate of filtration is directly proportional to the square of the area of a filtering surface. Therefore, higher the area of a filtering surface, higher will be the rate of filtration.
- The rate of filtration is inversely proportional to the viscosity of the filtrate. Therefore, higher the viscosity of the filtrate, lower will be the rate of filtration.
- The rate of filtration is inversely proportional to the resistance of a cake or filter medium. Therefore, higher the resistance of a cake or filter medium, lower will be the rate of filtration.

TYPES OF FILTRATION EQUIPMENTS

(a) Filters are generally divided into two major groups based on the function or goal of filtration (i.e., based on whether to produce a cake or sparkling liquid).

  (i) Cake filters.

  (ii) Clarifying filters.

- *Filters that retain appreciable quantities of filtered solids on the surface of the filter medium* are referred to as cake filters.
- *Filters that remove small amounts of solids to produce sparkling clear liquids* are referred to as clarifying filters or deep bed filters. These filters are commonly employed in water treatment.

(b) Filters may be classified according to the method of operation or operating cycle as

  (i) Batch filters

  (ii) Continuous filters

(c) Filters may be classified based on the driving force used for separation, e.g., gravity, pressure, vacuum or centrifugal.

- In filtration operation, the filtrate is forced to flow through a filter medium by virtue of a pressure difference across the medium. The pressure difference may be created by gravity, superatmospheric pressure on the upstream of the filter medium, sub-atmospheric pressure on the downstream of the filter medium or centrifugal force across the medium. Therefore, filters may be classified as
  (i) gravity filters, (ii) pressure filters,
  (iii) vacuum filters, (iv) centrifugal filters.

Industrial cake filters are usually classified as follows :

1. Batch (discontinuous) pressure filters
   e.g., filter press - plate and frame press, pressure leaf filters.
2. Continuous pressure filters
   e.g., pressure filter-thickener, continuous rotary pressure filters.
3. Batch vacuum filters
   e.g., vacuum nutsches, vacuum leaf filters.
4. Continuous vacuum filters
   e.g., rotary drum filters, vacuum precoat filters.
5. Centrifugal filters (batch and continuous)
   e.g., suspended basket centrifuge - top driven or bottom driven, continuous filtering centrifugals.

- The most important **cake filters** which will be referred to are : plate and frame filter press, rotary drum filter, and basket centrifuge.
- In many cases, in the chemical industry, it is the solids that are wanted.
- The factors to be considered while selecting equipment for filtration and operating conditions are :
  1. Properties of the fluid such as viscosity, density and corrosiveness/chemical reactivity.
  2. Nature of the solid which includes particle size, size distribution, particle shape and packing characteristics of solid particles.
  3. Concentration of solids in slurry, i.e., feed slurry concentration.
  4. Quantity of slurry to be handled and its value.
  5. Valuable product of operation.
  6. Necessity of washing the solids.
  7. Initial investment.
  8. Necessity of pretreatment of the slurry for ease in filtration.
  9. Cost of labour and power.

Primary Filter - Sand Filters

- Sand filters (clarifying filters) are used for water treatment and water purification. The medium of this filter is sand of varying grades. When we have to remove taste and odour, the sand filter may include a layer of activated carbon. There are several kinds of sand filters : rapid (gravity) sand filters, slow sand filters, pressure sand filters and upflow sand filters.