A Gateway to All Post Graduate Courses

An MHRD Project under its National Mission on Education throught ICT (NME-ICT)

Subject: Food Technology

Production of Courseware

e-Content for Post Graduate Courses

Paper No. : 04 Unit Operations in Food Processing

Module : 28 Mechanical separation-3: Filtration

Development Team

Principal Investigator	Prof. (Mrs.) Vijaya Khader, Ph.D Former Dean, Acharya N G Ranga Agricultural University
Paper Coordinator	Er. Dibyakanta Seth Asst. Professor, Tezpur University, Assam
Content Writer	Er. Dibyakanta Seth Asst. Professor, Tezpur University, Assam
Content Reviewer	Prof. (Mrs.) Vijaya Khader, Ph.D Former Dean, Acharya N G Ranga Agricultural University Dr. MC Varadaraj , Chief Scientist CSIR-CFTRI, Mysore

Description of Module	
Subject Name	Food Technology
Paper Name	04 Unit Operations in Food Processing
Module Name/Title	Mechanical separation-3: Filtration
Module Id	FT/UOFP/28
Pre-requisites	Mass transfer
Objectives	To know the principle of filtration process, To understand the design criteria in filtration process and To know the equipments and their operations in filtration.
Keywords	Filtration, specific cake resistance, constant pressure filtration, medium

28.1 Introduction

Filtration is a unit operation where separation of insoluble solids from a solid-liquid suspension is done with the application of mechanical or gravity force through a porous membrane. The solids are retained in the porous medium and form a layer, called *filter cake*. The liquid that passes through the porous medium which is free from any solid particles is called as *filtrate*. The porous medium is known as *filter medium*. The desired phase can be either cake or filtrate. In filtration of fruit juice, the filtrate is the clear juice which is the required phase. The driving force for the separation of the two phases may be gravity force or mechanical force. Pressure is created at the upstream or vacuum at the downstream to cause the flow of filtrate through the medium.

Clarification is a term used in food industries which is synonymous to filtration; the only difference is that, the suspension contains very few solid particles. Microfiltration is the separation of very tiny particles, which are impossible to separate by normal filtration. The limiting size of the solid particle for microfiltration is 0.1 mm.

28.2 Principle of Filtration

The driving force for filtration is most often the pressure difference. In the beginning of the filtration process, filtrate flows easily through the medium with least resistance. The rate of filtration which is the ratio of filtrate volume and time of filtration is high in the beginning. But, as the filtration progresses, the layer of cake deposition upstream gradually increases. So, now the filtrate not only ought to pass through the medium, but also it should cross the layer of cake. Hence, there is a constant pressure drop across the medium and it increases with time. After certain time, the filtration virtually stops. Two approaches can be made in filtration process. One can either follow filter process at constant pressure drop or at constant flow rate. If constant pressure is adopted, the rate of filtration gradually decreases. If later case is taken, one needs to increase the pressure with time to maintain a constant flow rate. The pressure drop depends on the two phases through which filtrate passes. These are filter cake and filter medium. So, the pressure drop is a function of cake characteristics like specific surface area and porosity and medium characteristics.

The total pressure drop ($-\Delta P$) is the summation of pressure drop across the cake ($-\Delta P_c$) and pressure drop across the medium ($-\Delta P_m$).

$$(-\Delta P) = (-\Delta P_c) + (-\Delta P_m) \qquad \ldots (28.1)$$

The negative sign indicates the pressure drop from high to low values.

Filtration capacity is the ratio of filtrate volume and the time of filtration cycle. The total filtration time is the addition of filtration time, washing time and transition time for assembling, adjustment of filter etc.

$$F_c = \frac{V}{t_c} = \frac{V}{t + t_w + t_{tr}} \qquad \ldots (28.2)$$

Where, t, t_w and t_{tr} are filtration time, washing time and transition time respectively.

28.3 Resistances during filtration

28.3.1 Filter cake resistance

The cake formed upstream contains pore spaces which form tiny channels through which filtrate can able to pass. Therefore, cake acts as a packed bed. Assuming the flow of filtrate inside the cake is in laminar region, we can express the flow by Poiseuille's equation.

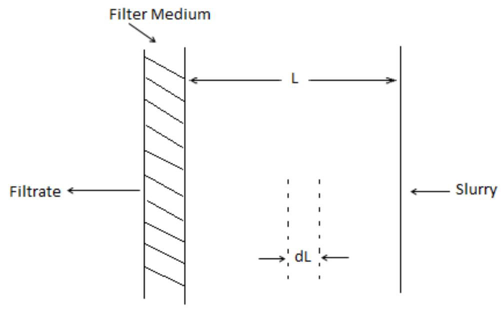


Fig.28.1: Filter cake section

Fig.28.1 shows a section of filter cake and medium with direction of filtrate flow. Let, the thickness of cake is *L* m, the filter cross sectional area is *A* m^2, the velocity of filtrate is *v* m/s.

The pressure drop per unit length of cake is given by Poiseuille's equation as shown below;

$$\frac{-\Delta P}{L} = \frac{32\mu v}{D^2} \qquad \dots (28.3)$$

Where, D is the diameter of small channel and μ is the viscosity of filtrate.

Carman-Kozeny relation is similar to equation (28.3) for laminar flow in packed bed. The equation is as shown below;

$$\frac{-\Delta P_c}{L} = \frac{k'\mu v(1-\varepsilon)^2 S_o^2}{\varepsilon^3} \qquad \dots (28.4)$$

Where, k' is a constant whose value is 4.17 for random particles of definite size and shape, ε is void fraction or porosity of cake and S_o is the specific surface area of particles per volume of solid particles.

The velocity of filtrate can be expressed as;

$$v = \frac{dV/dt}{A} \qquad \dots (28.5)$$

Where, dV/dt is the flow rate of filtrate with *t* as time of filtration, *A* is the filter area.

Substituting equation (28.5) in (28.4) we get,

$$\frac{dV}{Adt} = \frac{-\Delta P_c \varepsilon^3}{k'\mu(1-\varepsilon)^2 L S_o^2} \qquad \dots (28.6)$$

Doing a material balance in the cake section as shown in fig. 28.1, we obtain;

$$c_s(V + \varepsilon LA) = LA(1-\varepsilon)\rho_p \qquad \dots (28.7)$$

Where, c_s is the specific mass in *kg solid/m^3* of filtrate and ρ_p is the particle density in *kg/m^3* solid.

Eliminating *L* from equation (28.6) by substituting equation (28.7) we get;

$$\frac{dV}{Adt} = \frac{-\Delta P_c A}{\frac{k'(1-\varepsilon)S_o^2}{\rho_p \varepsilon^3}\mu c_s V} = \frac{-\Delta P_c A}{\alpha \mu c_s V} \qquad \dots (28.8)$$

$$\alpha = \frac{k'(1-\varepsilon)S_o^2}{\rho_p \varepsilon^3} \qquad \ldots (28.9)$$

Where, α is the specific cake resistance in *m/kg.*

As we see here specific cake resistance is a function of void fraction of cake and the specific surface area. It is also affected by the pressure, since pressure can affect void fraction. From the equation (28.8), we can see that, flow rate of filtrate is directly proportional to the pressure drop and inversely proportional to the volume of filtrate. If pressure drop is kept constant, the flow rate decreases with time, since volume of filtrate increases with time.

28.3.2 Filter medium resistance

The resistance offered to the filtrate flow by the medium is called filter medium resistance. The same filtrate which passes through the cake has to pass through the medium. So, an analogy can be built with cake resistance and application of *Carmann-Kozeny* equation proves to be valid.

The filtrate flow through medium wou ld be;

$$\frac{dV}{dt} = \frac{-\Delta P_m A}{\mu R_m} \qquad \ldots (28.10)$$

Where, R_m is the filter medium resistance in m^{-1}.

28.3.3 Total resistance in Filtration

The resistances of cake and filter medium are in series. So, the flow rate equations (28.8) and (28.10) can be combined to obtain the total resistance of the system. It will be;

$$\frac{dV}{Adt} = \frac{-\Delta P}{\mu(\frac{\alpha c_s V}{A} + R_m)} \qquad \ldots (28.11)$$

Filter medium resistance can be expressed in terms of a fictitious volume of filtrate. So, equation (28.11) can be modified as;

$$\frac{dV}{Adt} = \frac{-\Delta P}{\frac{\mu \alpha c_s}{A}(V + V_m)} \qquad \ldots (28.12)$$

Where, V_m is the volume of filtrate necessary to built up a fictitious filter cake whose resistance is equal to R_m .

The volume of filtrate *V* can be related to the mass of the cake deposited *M* as shown below;

$$M = c_s V = \frac{\rho c_x}{1 - m c_x} V \qquad \ldots (28.13)$$

Where, c_x is mass fraction of solids in slurry, *m* is mass ratio of wet cake to dry cake.

28.3.4 Compressibility of cake

If the specific cake resistance α does not change with pressure $-\Delta P$ and with thickness, the cake is said to be incompressible. Rigid solid particles keep the integrity of the cake and do not allow the porosity and specific surface to change by compression applied to the bed. In general, the solid particles are flexible and deformable.

So, the cake characteristics changes with pressure. Such cake is called compressible cake. Many empirical formula are used to calculate the specific cake resistance of compressible cakes. Almy and Lewis empirical formula is mostly used.

$$\alpha = \alpha_0(-\Delta P_c)^n \qquad \ldots (28.14)$$

Here, α_0 and n are empirical constants. n is called compressibility constant whose value is zero for incompressible cake. The value of n ranges between 0.1 and 0.8. The values can be found experimentally by plotting a graph between α and ΔP_c. The slope in logarithmic plot is the compressibility constant and the intercept is the constant α_0.

Another formula given by Ruth as follows;

$$\alpha = \alpha_0{}'[1 + \beta(-\Delta P_c)^{n'}] \qquad \ldots (28.15)$$

Here, $\alpha_0{}'$, β and n' are empirical constants which can be obtained from experiments.

28.4 Constant pressure filtration

The filtration process carried out at constant pressure drop is called constant pressure filtration. In constant pressure filtration the volumetric flow rate decreases with time. So, we need to derive the equation for volumetric flow rate from equation (28.11). By rearranging equation (28.11) we get,

$$\frac{dt}{dV} = \frac{\mu(\frac{\alpha c_s V}{A} + R_m)}{A(-\Delta P)} = \frac{\mu \alpha c_s}{A^2(-\Delta P)} V + \frac{\mu}{A(-\Delta P)} R_m \qquad \ldots (28.16)$$

In constant pressure filtration, the terms α and c_s are constants for incompressible cake. μ is the filtrate property which does not change and Area A is the dimension of filtration system. So, only variables are V and t in equation (28.16).

Time of filtration is found out by integrating above equation.

$$\int_0^t dt = \int_0^V \left[\frac{\mu \alpha c_s}{A^2(-\Delta P)} V + \frac{\mu}{A(-\Delta P)} R_m\right] dV$$

Or,

$$\int_0^t dt = \frac{\mu \alpha c_s}{A^2(-\Delta P)} \int_0^V V dV + \frac{\mu R_m}{A(-\Delta P)} \int_0^V dV$$

Or,

$$t = \frac{\mu \alpha c_s}{A^2(-\Delta P)} \frac{V^2}{2} + \frac{\mu R_m}{A(-\Delta P)} V$$

Denoting constants $K_1 = \frac{\mu \alpha c_s}{A^2(-\Delta P)}$ and $K_2 = \frac{\mu R_m}{A(-\Delta P)}$ and rearranging the above equation we get,

$$\frac{t}{V} = K_1 \frac{V}{2} + K_2 \quad \dots (28.17)$$

If we plot a graph taking V as abscissa and $\frac{t}{V}$ as ordinate, we obtain a straight line whose slope will be $\frac{K_1}{2}$ and intercept K_2 (Fig.28.2). After obtaining the values of K_1 and K_2 by graphical methods, we then calculate the specific cake resistance and filter medium resistance from K_1 and K_2 respectively.

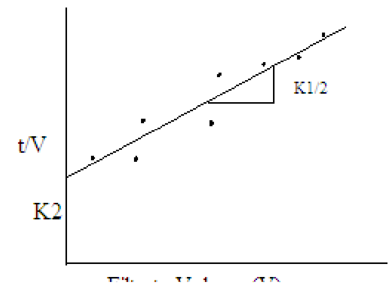


Fig.28.2 Determination of constants of filtration

28.5 Constant Volume filtration

The filtration process with a constant volumetric flow rate is called constant volume filtration. The pressure drop in this case is not constant rather it has to increase with time to maintain a constant flow rate.

Equation (28.11) can be rearranged to obtain the variable pressure head.

$$-\Delta P = \left[\frac{\mu \alpha c_s}{A^2}\frac{dV}{dt}\right] V + \left[\frac{\mu R_m}{A}\frac{dV}{dt}\right] \quad \dots (28.18)$$

The total volume of filtrate V is related to flow rate and total filtration time.

$$V = t\frac{dV}{dt} \quad \dots (28.19)$$

Combining equations (28.18) and (28.19) we get,

$$-\Delta P = \left[\frac{\mu \alpha c_s}{A^2}\left(\frac{dV}{dt}\right)^2\right] t + \left[\frac{\mu R_m}{A}\frac{dV}{dt}\right]$$

Or, $$-\Delta P = K_3 t + K_4 \quad \dots (28.20)$$

Where $K_3 = \frac{\mu \alpha c_s}{A^2}\left(\frac{dV}{dt}\right)^2$, and $K_4 = \frac{\mu R_m}{A}\frac{dV}{dt}$

The empirical constants K_3 and K_4 can be found out analogous to K_1 and K_2. If pressure drop is plotted against time, a straight line is obtained. The slope of the line will be the constant K_3 and the intercept will be K_4. The values of α and R_m can be found out from these constants.

28.6 Washing of cake

Washing of cake is an important step in filtration process. Unless it is washed, the porosity of cake decreases which affect the rate of filtration. Washing is carried out by a washing liquid passed through the cake either in the same direction as the filtrate flow or in opposite direction. The solid concentration of wash water initially is high and this concentration decreases with time as shown in fig 28.3. As shown in the figure, if the wash liquid follows the same path as the filtrate, the solid removal is as high as 90% and it abruptly decreases. In case the wash liquid following different path, the decrease is gradual. Plate and frame filter press generally is washed following the latter case. The washing area available in this case is half whereas the filtration resistance is double.

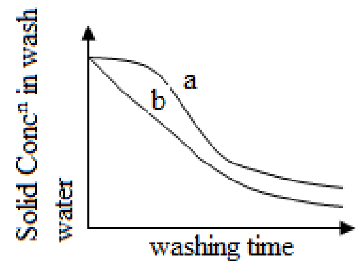


Fig.28.3 Concentration in wash water (a) same path, (b) different path

Equation (28.11) can be used for calculating the flow rate of wash water.

$$\frac{dV}{A_w dt} = \frac{-\Delta P}{\mu\left(\frac{\alpha c_s V}{A_w} + R_m'\right)} \quad \ldots (28.21)$$

Where, A_w is the area available for wash water.

In plate and frame filter since the washing area is half and filter resistance is double i.e.

$$A_w = \frac{A}{2} \text{ and } R_m' = 2R_m$$

We can rewrite the equation (28.21) as

$$\frac{dV}{Adt} = \frac{1}{4}\frac{-\Delta P}{\mu\left(\frac{\alpha c_s V}{A} + R_m\right)} \quad \ldots (28.22)$$

We can see here, the flow rate of wash water is one fourth of the filtrate flow rate at a constant pressure drop. The washing time can be calculated as,

$$t_w = \frac{V_w}{dV_w/dt} \quad \ldots (28.23)$$

Where, V_w is the amount of wash water required in the washing step.

28.7 Filtration Equipments

28.7.1 Depth filters

Depth filter is one where the solids take the space of the pores instead of forming cakes on the surface. Sand filter is a common type of depth filter used to purify water (Fig.28.4). It is suitable for filtration of suspension with less solid concentration. The sand is filled from the bottom in pattern of decreasing size. Flocculants are usually added to water before filtration. The filtration continues till the solid particles fill the sand pores. Back washing is possible only when the suspended particles are non-adhesive to the sand particles.

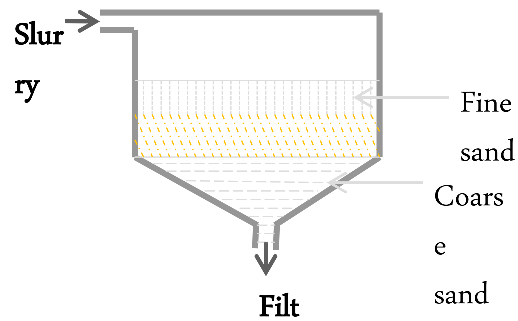


Fig.28.4: Sand bed Filter

28.7.2 Surface filters

In surface filter or barrier filter, pressure difference is needed between the upward and downward side of the medium. One can apply a positive pressure at feed side or a vacuum pressure at filtrate side to maintain the filtrate flow. Surface filters are categorised as pressure filters, vacuum filters and centrifugal filters. The most common type of filter used is plate and frame filter press and among vacuum filters rotary vacuum filters.

Plate and frame filter press

Plate and frame filter press consists of a series of plates stacked in a horizontal or vertical plane so as to form channels as shown in fig.28.5. Alternate frames are provided through which slurry is fed. Filter medium or cloth is wrapped over the plates. The slurry is pumped to the system which enters the individual frame. The clear filtrates pass through the medium leaving suspended solids in the form of cake inside the frame area. The process continues till the frame area is completely filled with cake and no further slurry can enter to it. The clear filtrate is collected through a pipe and drained out.

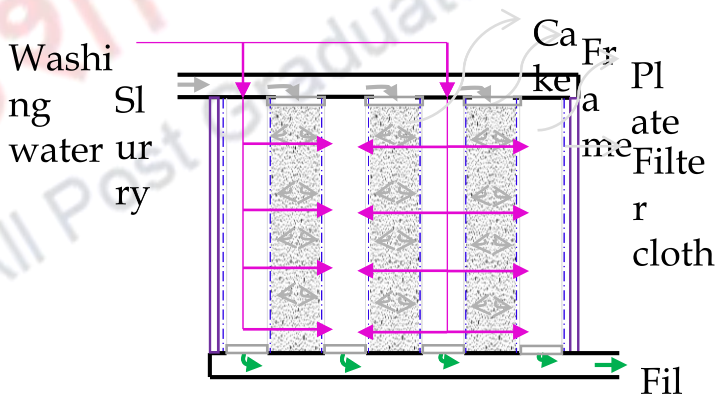


Fig.28.5: Plate and Frame Filter Press

Washing is done by providing wash water plates alternate to the filtration plate. Water is allowed to pass through the inlet of the wash water plate. Wash water travels through the ports of the plates via the medium through the whole section of the frame and thus cake is removed from the frame area.

Plate and frame filter is a batch processing system. If higher throughput is required, it is not a suitable option. However, it can be used for high pressure operation. The operation is simple but the washing of cake intermittently is required. So, a long processing time is required.

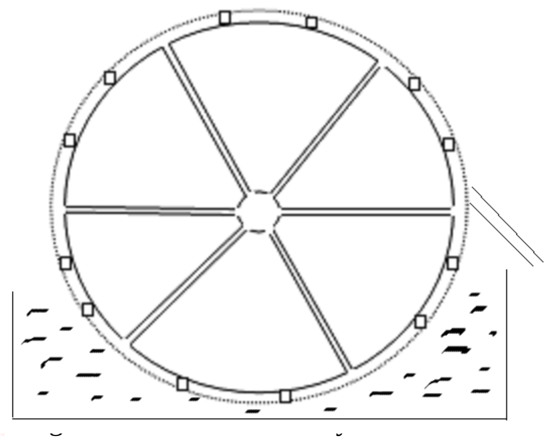
Cartridge filter

Cartridge filters are a series of filtering elements attached to a suction pipe. The set of filter is placed on the suspension flowing stream. The perforated element sucks in the filtrate and the suspended solids are left in the stream.

The use is limited to a small solid removal like in separation of solids from water before spraying through nozzle.

Continuous rotary vacuum filter

Continuous rotary vacuum filter consists of a cylindrical drum rotated horizontally. It contains hollow tubes inside the drum that lead to a central concentric pipe where vacuum is maintained. The filtering medium is wrapped over the drum which is separated by intermittent guide. The filtrate is sucked to the radial channels via the medium. The cake collected on the surface of the medium is scrapped away by a blade mounted at the end of the cycle.



In vacuum filters, the pressure drop is limited to less than 100 kPa. For this reason the vacuum filters are not in the following cases.

- High viscous slurry
- Slurry containing small particles
- Rapid filtration process

Centrifugal filter

Centrifugal filter is basically a basket with perforated wall rotated by a shaft connected centrally. The inner wall is wrapped with filtering medium. When basket is rotated, slurry is forced to move towards the wall. The filtrate thus comes out from the perforated wall and collected in an outer basket. The rate of filtration depends on the centrifugal force applied to slurry and the suspended solids. In food processing centrifugal separation is mostly adopted for separation of sugar crystals from the mother liquor. Since, no pump is required here, the operation cost is less compared to plate and frame filter press.

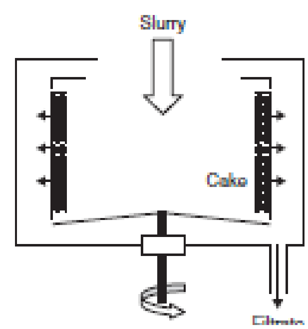


Fig.28.7: Centrifugal filter

28.8 Filter medium and aid

The requirements of filter medium are,

i. It should efficiently remove the suspended solids giving a clear filtrate,
ii. There should not be any clogging of pores during filtration,
iii. The washing of cake from the medium should be easy, and
iv. It should have sufficient strength and chemically inactive to the suspension.

The examples of some industrially used filter media are woollen cloth, glass cloth, paper, felted pads of cellulose, metal cloth and nylon cloth. The ragged fibers of natural materials are used to separate very fine particles.

Filter aids are chemical substances used to increase the porosity of cake. These are primarily composed of silica gel. In some cases cellulose, asbestos and other inert porous solids are used. The filter aids can be used either by mixing it to the suspension before filtration or by putting a layer of these materials over the medium as precoat. The limitation of the application of the aid is in the filtration process where cake is discarded.

References

1. *Unit Operations in Food Engineering* (1st Edition), Albert Ibarz and Gustavo V. Barbosa-Canovas, CRC Press, NY, Publ., 2003.
2. *Food Process Engineering and technology,* Zeki Berk, Elsevier Inc. New York., Publ., 2009.
3. *Fundamentals of Food Process Engineering* (3rd Edition), Romeo T. Toledo, Springer Science, 2007.