Paper No. : 04
Paper Title: Unit Operations in Food Processing
Module- 27: Mechanical Separation 2: Centrifugal Separation

27.1 Introduction

Centrifugal separation or centrifugation is a process in which two heterogeneous mixtures of phases are separated from each other by the application of centrifugal force. The phases may be solid, liquid or gas. The basic principle governing the separation of the heterogeneous phases is the density difference. The slurry when allowed to rotate along an axis inside a bowl, the force exerted on each particle varies. The force variation is due to difference in mass or density, the distance of particle from the axis of rotation and the rotational speed.

Suppose a particle of mass 'm' kg moves in a circular path, the tangential velocity at any point in the path is 'v' m/s. If the particle is at r distance from the axis of rotation, the angular velocity will be

$\omega = \frac{v}{r}$ rad/s

The angular acceleration, $a_c = r\omega^2$ m/s^2.

The centrifugal force is the product of mass and angular acceleration. So,

$F_c = ma_c = mr\omega^2$

Since, $\omega = \frac{v}{r}$, $F_c = mr\left(\frac{v}{r}\right)^2 = \frac{mv^2}{r}$

Normally, the angular velocity is expressed as $\omega = \frac{2\pi n}{60}$, where, '$n$' is the revolution per minute.

Putting the above relation in F_c ,

$$F_c = mr\left(\frac{2\pi n}{60}\right)^2 = 0.0109\, m\, r\, n^2$$

$$\frac{F_c}{F_g} = \frac{0.0109\, m\, r\, n^2}{mg} = 0.0011\, r\, n^2$$

Hence, the centrifugal force is 0.0011 r n^2 times greater than the gravitational force. The centrifugal force is sometimes expressed as the multiple of 'g' i.e. acceleration due to gravity.

From the relation it is clear that, the centrifugal force depends upon the radius and speed of rotation and the mass of the particle. Keeping the radius and speed of rotation constant, we can say that the centrifugal force acting on heavier particle is higher than that of lighter particle. Therefore, the heavier particles are displaced from the slurry towards the periphery of the bowl and the lighter particles are moved towards the centre.

It is needless to mention that, a food mixture carries different phases in different forms. Fat in milk is a mixture of liquid in liquid. Sugar crystals in syrup, is a solid-liquid mixture. The milk powder in air is a solid-gas mixture. The basic principle in separation of the phases is same, but the design of the bowl, the location of outlet for each phase in the centrifuge varies.

27.2 Solid-liquid separation

27.2.1 Centrifugal settling

There are numerous examples of solid-liquid mixture in food system. During preparation of starch, the starch particles are suspended in water. The fruit fibers are suspended in juice. The dirt particles need separation from the liquid foods. Sugar is crystallized from the solution and separated thereafter. The solid matter either floats or settles in the tank in due course of time because of the density difference between the two phases. The rate of settling depends on the density of particle, density of liquid, viscosity of liquid and the gravitational force. If gravitational force is used as the main driving force, it takes longer time to get settled. So, to achieve quick settling centrifugal force is used, and the process is called centrifugal settling.

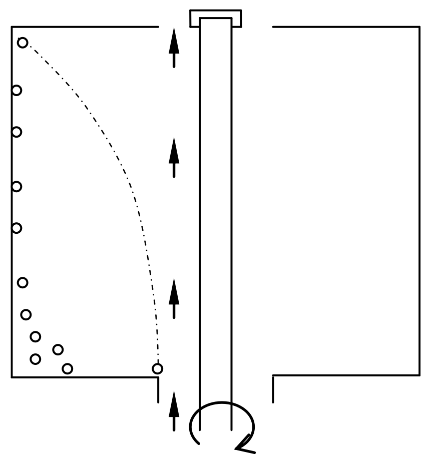

Fig.27.1 Settling of particles in a centrifuge

In a centrifugal bowl if slurry is allowed to centrifuge, the solid particles follow a trajectory path as shown in fig.27.1. A particle settles if it gets sufficient residence time to reach the wall of the bowl, otherwise, it exits through the outlet. The residence time depends on the angular acceleration and the size of the particle. The settling velocity of a particle at radial distance r is given by;

$$v_{tr} = \frac{\omega^2 r d^2 \Delta\rho}{18\mu} \quad \text{….. (1)}$$

Where, v_{tr} is the terminal velocity of the particle in m/s, ω is the angular velocity in rad/s, d, the diameter of particle, Δρ, the density difference between the slurry and the solid particle in kg/m^3, μ is the viscosity of slurry in Pa.s. If r_{max} is the maximum distance a particle can cover during its residence time and r_{min} is the starting point of the particle when it enters the bowl of length *l* m, a relation of the flow rate *Q* m^3/s of the slurry and the minimum diameter of the particle can be derived.

Since, $v_{tr} = dr/dt$, equation (1) can be rewritten as

$$dt = \frac{dr}{v_{tr}} = \frac{18\mu}{\omega^2 d^2 \Delta\rho} \frac{dr}{r}$$

Integrating both sides of the equation $\int_0^t dt = \frac{dr}{v_{tr}} = \frac{18\mu}{\omega^2 d^2 \Delta\rho} \int_{r_{min}}^{r_{max}} \frac{dr}{r}$

Or, $t = \frac{18\mu}{\omega^2 d^2 \Delta\rho} \, ln \frac{r_{max}}{r_{min}}$ …. (2)

where t is the total residence time of the particle.

But, the residence time t is equal to the volume of the bowl divided by the volumetric flow rate of the slurry i.e. $t = \frac{V}{Q} \ldots$ (3)

V is the volume of slurry inside the bowl.

$V = \pi l(r_{max}^2 - r_{min}^2)$ ….. (4)

Substituting equation (3) and (4) in equation (2), we get

$$Q = \frac{\omega^2 d^2 \Delta\rho}{18\mu \ln\frac{r_{max}}{r_{min}}} \left[\pi l(r_{max}^2 - r_{min}^2)\right] \ldots.(5)$$

From the equation (5), it is concluded that, a particle of minimum diameter *d* will settle on the bowl with a volumetric flow rate of Q m^3/s. A particle with diameter less than this will not settle and will exit along the flow.

27.2.2 Centrifugal filtration

The filtration process is accomplished by allowing the slurry through a porous medium. The rate of separation depends on the particle size of the slurry, the pore size of the filter medium and the pressure differential at both side of the filter medium. Moreover, the rate of filtration drastically changes with the thickness of the cake formed during filtration. Instead of induced pressure differences in the process, centrifugal force is applied in some cases. The filtration process that uses centrifugal force is called centrifugal filtration. In almost all the centrifugal filters, the filters are attached concentrically to the cylindrical bowl and the flow of liquid is horizontal unlike normal filtration process. The centrifugal filters can be batch or continuous types.

Batch centrifugal filters

A cylindrical bowl perforated at the wall is suspended by a cylindrical shaft. The whole unit rotates with the rotation of the central shaft. The rotating unit is stationed inside a stationary casing (Refer multimedia). The perforated wall is lined with the filter medium of required pore size as per requirement. The filter medium gets physical support by the wall; thereby tearing of filter medium is avoided. The slurry is fed from the top to the rotating bowl, necessarily from the centre. Due to rotation, the slurry take a trajectory path, eventually the vertically moving slurry moves in horizontal direction and meets the filter medium perpendicularly. The particles greater than the pore size of filter medium cannot pass through the medium and get deposited at the inner wall of the medium, which is called as cake. The thickness of the cake increases radially with time and the pressure differential decreases which reduces the rate of filtration. The clear filter passes through the medium and collected from the outer casing. When the filtration decreases drastically due to deposition of cake, the wash liquid may be sprayed to the cake at high speed for removal at the bottom outlet provided. Sometimes hydraulically operated cutting knives are used to remove the cakes from the system. In the batch process the cycle time varies from 3-30 min.

Continuous centrifugal filters

The continuous filtration system is a slight modification of batch system. The bowl is made conical instead of cylindrical. The advantage of inclination is felt by splitting the force into two components viz.

vertical and horizontal. The vertical force pushes the slurry from bottom to top and discharge the solids from the lid of the bowl. The horizontal force purges the liquid phase to filter out from the bowl. In this way when the mixture is pushed up the concentration of solids increases. One disadvantage of this continuous process is its severity of forces on the product due to relatively high speed of rotation, thereby causing the damage to the product. One common use of this continuous system is in sugar industries where sugar crystals are separated from the syrup.

27.3 Liquid-liquid separation

Two immiscible liquids finely dispersed as the state of emulsion are physically not stable. Because of density differences, the lighter liquid separates from the heavier liquid, if allowed to stand for some time. Milk is a good example of emulsion where fat is in the finely dispersed state where as the skim milk is in continuous phase. For the processes where separation of these two immiscible liquids is intended, application of centrifugal force to accelerate the fast separation is a good alternative.

The controlling point in the separation process is the liquid-liquid interface which separates the two phases. The relative position of the line of interface is best described by a force balance on the line. Here we shall discuss the separation of two phases inside a tubular bowl centrifuge.

If r is the radial distance of a liquid section, the centrifugal force action on the section will be;

$F_c = mr\omega^2$

The differential force is represented as $dF_c = dmr\omega^2$ …… (6)

The pressure exerted on the annular space of the tubular bowl centrifuge is;

$\frac{dF_c}{A} = \frac{dmr\omega^2}{2\pi rl}$ ….(7)

Where, *l* is the length of the tubular bowl and A is the area of annular space.

But, the differential mass dm is represented as;

$dm = (2\pi lrdr)\rho$ … (8)

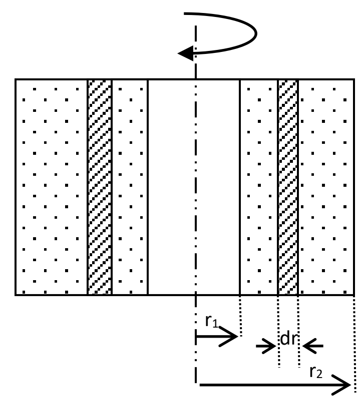

Fig.27.2 Rotating annular mass

Putting the value of dm in equation (7) we get,

$dP = \frac{(2\pi lrdr)\rho\, r\omega^2}{2\pi rl} = \omega^2\rho rdr$ …. (9)

Integrating equation (9) we get,

$P_2 - P_1 = \omega^2\frac{\rho}{2}(r_2^2 - r_1^2)$…(10)

There exists a layer of interface between heavy and light liquid phase, where the equilibrium is maintained. If the radial distance of the layer from the axis of rotation in the annular space is r_e, we get the following expression.

$$\omega^2 \frac{\rho_l}{2}(r_e^2 - r_1^2) = \omega^2 \frac{\rho_h}{2}(r_e^2 - r_2^2) \ldots. (11)$$

Where, r_e is the radius of interface in equilibrium, r_2 the radius of heavy phase and r_1 the radius of light phase, ρ_l and ρ_h are the densities of light and heavy phase respectively.

Simplifying equation (11) we get,

$$r_e^2 = \frac{\rho_l r_1^2 - \rho_h r_2^2}{\rho_l - \rho_h} \ldots (12)$$

In the design of tubular centrifuge equation (12) is helpful. The equilibrium radius is a factor of relative distances between lighter and heavier liquids and the densities of both the liquid phases. The values of r_1 and r_2 can also be varied independently to provide an optimum separation condition.

27.4 Solid-gas separation

Solid particulates separation from a gas stream is very common phenomenon in food processing operations. The separation of milk powder from the drying air stream coming from the drying chamber of a spray dryer after drying is a good example of solid-gas separation. The peripheral attachment required for this operation to accomplish is called cyclone separator (Fig.27.3). The cyclone consists of a vertical cylindrical section with a conical section attached at the bottom. A concentric vertical cylinder guides the solid free air from the centre of the cyclone to air exhaust. The solid-gas mixture is allowed to enter tangentially near the top of the cyclone. The pressurized mixture thus forms a vortex inside the cyclone due to rotational movement. In this way the centrifugal force is developed. The solid particulates get concentrated towards the wall of the cyclone and settle down at the conical section by centrifugal force. So, this section of the cyclone works a centrifugal settler. The solid free air stream form small vortex near the centre and moves upward. The interesting fact about the cyclone separator is that, no mechanical energy is applied to induce centrifugal force inside the cyclone. The principle of separation is same as in centrifugal separator. The efficiency of separation depends on the size of particles, the diameter of cyclone and the air velocity. The finest particles cannot reach to the wall of cyclone and drifted with the exhaust air. The heavier particles easily settle down and collected at the bottom of the cyclone.

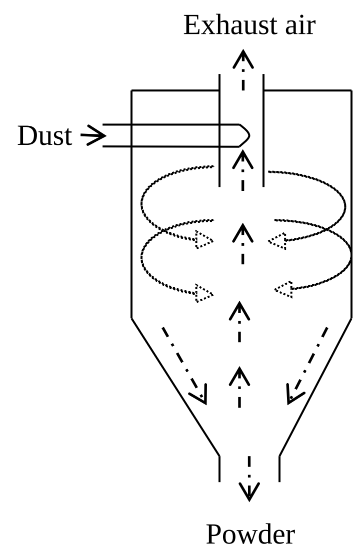

Fig.27.3 Cyclone separator

27.5 Application of centrifugal separation

The application of centrifugal separation is enormous because of its increased rate of separation. Dairy industry is one which utilizes the principle of centrifugation since the inception of this technology. Here is the list of some applications of centrifugal separation processes adopted in food processing.

i. Separation of milk fat from whole milk to get cream and skim milk is an age old process. Centrifugal separators are used for this purpose.

ii. In cheese industries, milk after coagulation, the separation of curd and whey is done in centrifugal clarifier. The difference between the separator and clarifier is that, the clarifier does not have intermediate holes for upward climbing of liquid.
iii. In fruit processing industries, the pulp is separated to get clear juice.
iv. Separation of starch from starch suspension is done by centrifugal separator.
v. Yeast after growth in growing medium is separated from medium by centrifugal separator.
vi. Centrifugal separation is a preferred method during edible oil processing, at different stages of refining. The oil is separated from the aqueous phase by mechanical separators.

References

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