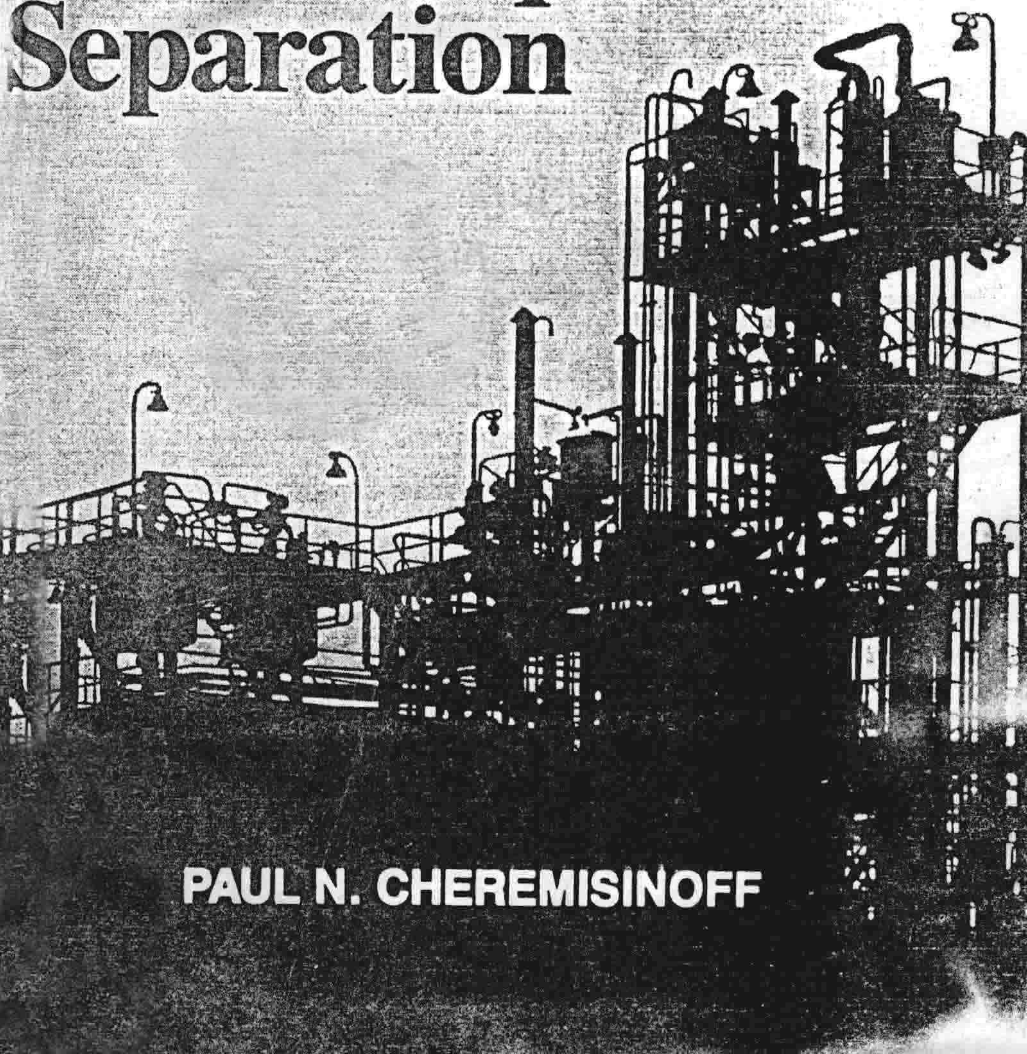
PROCESS ENGINEERING HANDBOOK SERIES

Solids/Liquids Separation



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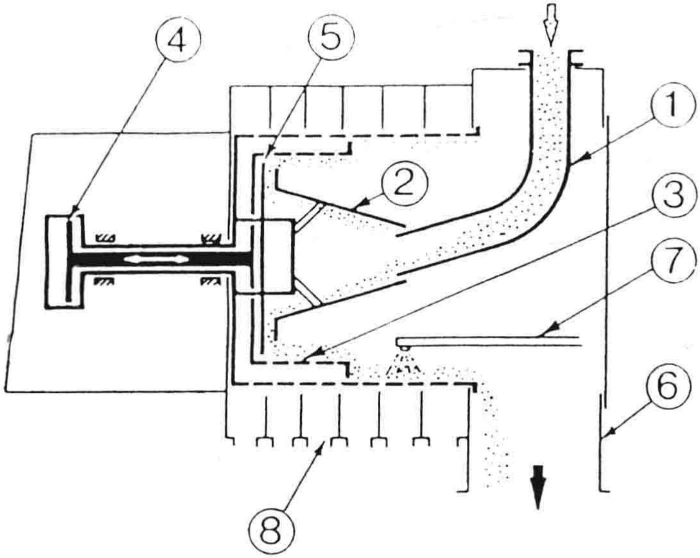

FIGURE 6.4. Two-stage push-type centrifuge—feed enters through the inlet pipe (1) and accelerating cone (2) and is introduced on the first-stage basket (3) where the solids are retained on the sieves. The first-stage basket, actuated by the hydraulic pushing mechanism (4) reciprocates under a static pusher plate (5) to advance the cake from the first to the second stage on the back stroke. The forward stroke of the first basket pushes the cake off the second basket and into the cake chute (6). In models with more than two stages, alternate baskets telescope, easing the cake from stage to stage. In multistage units, multiple washes can be employed (7), and mother and wash liquors can be separately discharged, if desired, through a compartmented effluent chamber (8).

Scroll-Screen Centrifuge

The scroll-screen-type centrifuge consists of a conical basket that can be either horizontal or vertical and contoured to fit inside the cone. Depending upon the product handled and the angle of the cone, the scroll can be used either to retard the advance of the solids through the basket or to transport the solids down the basket. They are not as susceptible to feed concentration as the push-type centrifuge, although solids losses and capacity will be greatly affected by feed concentration. Relatively high capacities are obtained at a moderate price in this type of equipment. The effectiveness of washing is relatively low, both because of the short retention time in the machine and the relatively poor distribution of wash over the surface of the product being transported. When fragile crystals are handled, the action of the scroll across the surface of the screen tends to break the particles and drive them through the screen. Where fine separations are employed below

300μ (50 mesh, relatively fine screens are employed and if the product being handled is abrasive, short screen life can often be anticipated.

In a scroll-screen centrifuge, the feed comes into the feed pipe at the top of the cone at the small diameter where the bulk of the mother liquor is removed as the solids accelerate down the screen. The scroll is run at a speed either slower or faster than that of the bowl, the differential movement generally being supplied by a cyclo gear, which provides the differential movements between the bowl and the scroll. The sizes offered vary from 250 mm (10 in.) in diameter, with a capacity over 3,000 lb/hr, up to large machines employed typically in the coal industry of 900 mm (36 in.), which handle 20–30 ton/hr.

Another type of screen centrifuge is illustrated in Figure 6.5. This type of centrifuge does not employ a scroll but has a series of baffles that rotate at the same speed as the basket to slow the path of the solids as they progress along the basket and over the screen. This provides the desired retention time so that the desired dewatering can be accomplished. The retention time is regulated by adjusting the baffles. Performance is similar to other scroll screen machines and eliminates the possible degradation of particles caught between the scroll operating at a different speed than the basket.

Basket Centrifuges

The basket centrifuge represents the original type centrifuges used for liquid-solid separations. They are used extensively throughout the process industries worldwide. Most of the centrifugals for sugar processing and crystallization are of this type. They are manufactured in an "overdriven" type, with the motor and shaft above the basket and the basket suspended from an overhead frame, or an underslung type, in which the basket is driven from below, usually suspended with a three-point suspension from the frame.

Such machines have been developed so that they are available with completely automated systems and can be fully programmed to go through the desired cycles without operator attention. They are constructed with perforated baskets, in which a filter medium is installed. The liquor filters through the basket or imperforate types where the solids are sedimented against the bowl wall and the effluent overflows the basket top ring. Generally, machines employed in the chemical and pharmaceutical industry are the perforate type used for separation of crystalline or other discrete particles, whereas the imperforate type is generally employed in waste treatment applications and for the dewatering of very fine particles and/or sludges. These machines are batch types, and the cycles are almost infinitely variable. Cycles can be varied to achieve the desired performance.

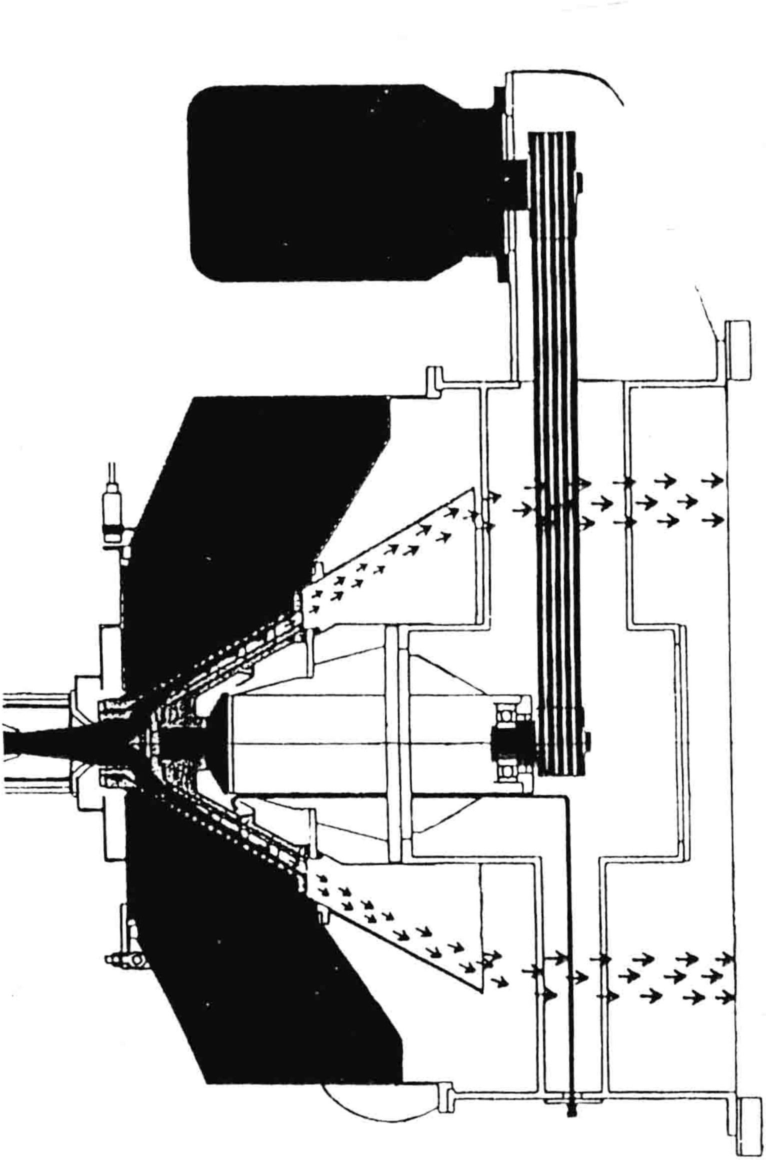

FIGURE 6.5. *Screening centrifuge.*

The basket provides a good surface for washing the material contained therein. Long spin times can provide maximum dryness.

The baskets are generally built from 12–48 in. in diameter, the largest generally employed. These machines will usually be able to handle a capacity of about 12 ft^3 of product per cycle. The electrical or hydraulic systems on the underdriven machines generally have a minimum cycle of about 12–15 min. Unloading is accomplished at a speed of about 50 rpm. Overdriven machines with very large motors can be designed for shorter cycles.

This type equipment is widely employed in the fine chemical and pharmaceutical industry, where products are produced on a batch basis and many different products are produced with the same equipment. The variable feature of the cycle enables one to change the cycle from batch to batch or product to product as required.

Peeler Centrifuge

The peeler centrifuge is another type of basket centrifuge. The basket usually rotates on a horizontal axis. The difference between this equipment and the previously described basket is that, on the peeler, the basket unloads the cake at full speed. The knife moves into the basket to unload the solids at the full operating speed of between 800–1,200 rpm. This provides the capability of short cycles, usually in the range of 2–5 min, and provides for higher capacities than low-speed unloading baskets. Longer cycles can be employed; however, generally, if these exceed 10 min, an underdriven machine is often the more economical choice.

This type equipment is still used in starch processing. The peeler provides close to continuous operation at relatively high capacities. In recent years, many of the applications where this equipment was formerly employed are now done on continuous centrifuges.

Miscellaneous Centrifuges

There are several types of centrifuges that employ a conical basket. One of these is commonly known as a "skid pan," which consists of a conical basket rotating on a shaft fed at the small end of the cone. The liquid passes through a screen, and the particles slide up the side of the basket where they are discharged. These were developed in the sugar industry where the feed conditions are highly controlled and consistent. The travel of the particles up the side of the basket depends on the feed consistency and the size and shape of the particles. In attempts to employ these in the chemical industry, where the solids and feed consistency are variable, the use of this equipment has had very limited success.

Another centrifuge of this type is an oscillating centrifuge. This is similar to the skid pan, in that it has a conical basket, but, in addition, the basket is oscillated at approximately 2,000 cycles per minute, which helps transport the solids up the basket. This type of centrifuge is widely employed in the coal industry and is used extensively for dewatering of 6 × 0.5 mm (1/4 in. × 28 mesh) coal. It is built in basket sizes from 1,000–1,250 mm (40–48 in.). It has a capacity on fine coal (6 × 0.5 mm) of 80–150 ton/hr and requires a good, prethickened feed, usually 75–80% solids, and is only effectively employed on materials in the +0.3-mm (48-mesh) range.

Some of this equipment has been employed in the potash industry for separation of coarse potash and coarse salt. They also have been used in the production of sea salt.

Another centrifuge of a similar type, again having a conical basket, is a tumbler in which the basket rotates in a manner designed to transport the solids up the basket is a tumbler in which the basket rotates in a manner designed to transport the solids up the basket. These have been employed mainly in Europe.

SEDIMENTATION CENTRIFUGES

Sedimentation centrifuges, as the name implies, are settling devices employing centrifugal force for the acceleration of settling effects. All sedimentation centrifuges require the solids to be heavier than the liquid to effect the separation. There are a variety of types employing different means of removing the solids from the centrifuges. Many types are required for the great variety of separation problems that exist in the process industries. They are not usually sensitive in their solids handling capacity to feed concentration because the liquid does not have to filter through the solids or a filter medium. They are employed for a wide variety of separations from relatively coarse particles of 6 mm (1/4 in.) down to submicron sizes. Flocculants are often employed to assist in the agglomeration of the particles to aid in the settling for very fine materials and many waste sludges.

Another approach to the separation of solids from suspensions in a centrifugal field is through the use of sedimentation centrifuges. As in cyclones and hydrocyclones, particles of the heavier phase "fall" through the lighter phase, away from the center of rotation. In centrifuges, liquid (or gas) and solids are acted on by two forces: gravity acting downward and centrifugal force acting horizontally. In commercial units, however, the centrifugal force component is normally so large that the gravitational component may be neglected.

The magnitude of the centrifugal force component is defined by the ratio

$R_c/G = \omega^2 r/g$, which is referred to as the "relative centrifugal force" (RCF) or centrifugal number, N_c, where $R_c = m\omega^2/2$ or $R_c = mv^2/2$ is the centrifugal force and $F_g = mg$ is the gravitational force. The RCF typically varies from 200 times gravity for large-basket centrifuges to 360,000 for high-speed tubular-gas centrifuges and ultracentrifuges.

For liquid-solid separations, centrifugal force may be applied in sedimentation-type centrifuges, centrifugal filters, or a combination of both.

Sedimentation-type centrifuges also are used for size or density classification of solids, the separation of immiscible liquids of different densities, and concentrating gases of different molecular weights. The principles of centrifugation are illustrated in Figure 6.6. In Figure 6.6 (a) a stationary cylindrical bowl contains a suspension of solid particles in which

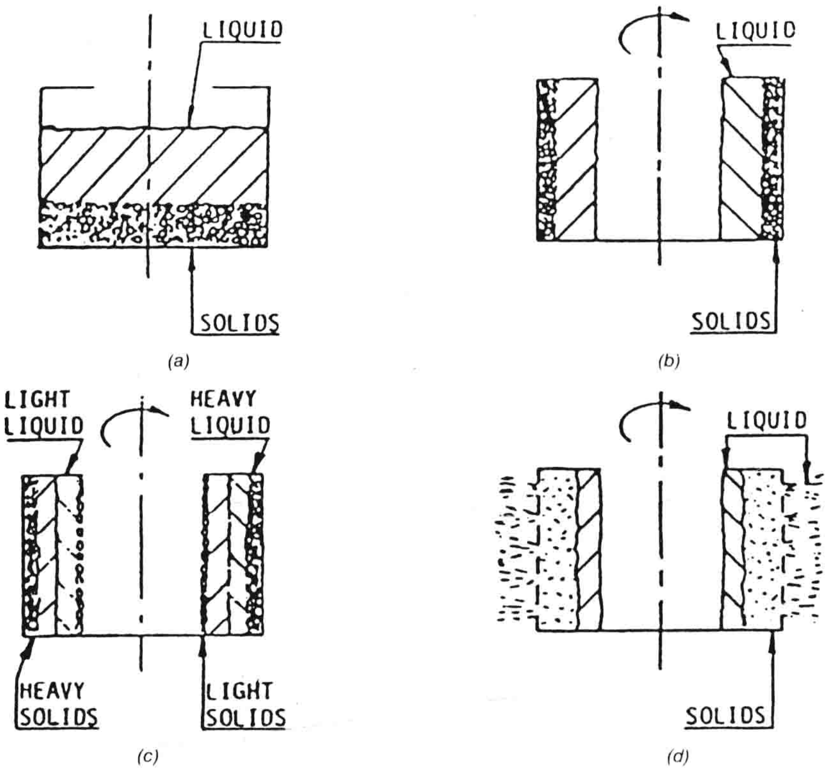

FIGURE 6.6. (a) Stationary cylindrical bowl (liquid plus heavy solid particles); (b) rotating cylindrical bowl (liquid plus heavy solid particles); (c) rotating cylindrical bowl (two liquids plus light and heavy solid particles; (d) rotating perforated bowl.

the particle density is greater than that of the liquid. Because the bowl is stationary, the free liquid surface is horizontal, and the particles settle due to the influence of gravity. In Figure 6.6(b), the bowl is rotating about its vertical axis. Liquid and solid particles are acted on by gravity and centrifugal forces, resulting in the liquid assuming a position with an almost vertical inner surface (free interface).

If the suspension consists of several components, each with different densities, they will stratify with the lightest component nearest the axis of rotation and the heaviest adjacent to the solid bowl wall [Figure 6.6(c)].

In Figure 6.6(d), the bowl wall is perforated and lined with a permeable membrane, such as filter cloth or wire screen, which will support and retain the solid particles but allow the liquid to pass through due to the action of centrifugal force.

The main components of a centrifuge are

- a rotor or bowl in which the centrifugal force is applied to a heterogeneous system to be separated
- a means for feeding this system into the rotor
- a drive shaft
- axial and thrust bearings
- a drive mechanism to rotate the shaft and bowl
- a casing or "covers" to contain the separated components
- a frame for support and alignment

There are three main types of centrifuges, which may be classified according to the centrifugal number and the range of throughputs or the solids concentration in suspension that can be handled. The first of these is the *tubular bowl centrifuge.* This type has a centrifugal number in the range of 13,000 but is designed for low capacities (50–500 gph) and can handle only small concentrations of solids.

The second is the *solid bowl centrifuge*, with maximum bowl diameters ranging from 4–54 in. The larger diameter machines can handle up to 50 ton/hr of solids with a centrifugal number up to 3,000. Similar centrifuges are manufactured with a perforated wall on the bowl. These machines operate exactly like filters, with the filtrate draining through the cake and bowl wall into a surrounding collector.

The third type is the *disk bowl centrifuge*, which is larger than the tubular bowl centrifuge and rotates at slower speeds with a centrifugal number up to 14,000. These machines can handle as much as 30,000 gph of feed containing moderate quantities of solid particles.

The migration of particles in sedimentation centrifuges is radially toward or away from the axis of rotation, depending on whether the density of the dispersed particles is greater or less than that of the continuous phase.

TABLE 6.2. Classification of Sedimentation Centrifuges.

Flow Arrangement	Centrifuge Types
Liquid-batch	Analytical and clinical
Solid-batch	Ultra and preparatory miscellaneous batch
Liquid-continuous	Tubular bowl
Solids-batch	Multipass clarifier
	Disc (solid wall)
	Basket type (solid wall)
Liquid-continuous	Disc-valve discharge
Solids-intermittent	Disc-automatic opening
Liquid-continuous	Disc-peripheral nozzles
Solids-continuous	Disc-light solid-phase skimmer, continuous decanter

There must be a measurable difference between the density of the continuous and dispersed phases to provide effective separation.

In commercial machines, the discharge of the liquid or separated liquid phases is performed almost always in a continuous fashion. The heavy solid phase deposited against the bowl wall is discharged and recovered intermittently, manually, or by action of an unloader knife or skimmer; continuously by action of a differential screw conveyor; or intermittently or continuously with a portion of the continuous phase through openings in the wall of the bowl. Variations are summarized in Table 6.2. Manual solids removal units can operate continuously up to 1 hr and generally only require a few seconds for a fully automated intermittent operation. In systems in which solids have a lesser density than the continuous phase, particulates can be removed continuously from the surface of the liquid via a skimming tube or exit as an overflow from the bowl with a portion of the continuous phase.

Solid Bowl Centrifuges

One of the most versatile of continuous centrifuges is the solid bowl centrifugal, which has been employed widely in the process industries.

Figure 6.4 shows a cutaway of this machine, and the following is a description of how it operates. The two principal elements of the solid bowl centrifugal are the rotating bowl, which is the settling vessel, and the conveyor, which discharges the settled solids. The bowl has adjustable overflow weirs at its larger end for discharge of clarified effluent and solids discharge ports on the opposite end for discharging dewatered solids. As the bowl rotates, centrifugal force causes the slurry to form an annular pool, the depth of which is determined by the adjustment of the effluent weirs. A portion of the bowl is or reduced diameter so that it is not submerged in the pool and thus forms a drainage deck for dewatering the solids as they are conveyed across it.

Feed enters through a stationary supply pipe and passes through the conveyor hub into the bowl itself. As the solids settle out in the bowl, due to centrifugal force, they are picked up by the conveyor scroll and carried along continuously to the solids outlet. At the same time, effluent continuously overflows the effluent weirs. If washing is required, wash liquors enter the centrifuge through a separate pipe and are sprayed onto the solids as they pass across the drainage deck.

Solid bowl centrifuges are made in sizes from 150–1,350 mm (6–54 in.) in diameter. They are made in lengths from 300–3,500 (12–140 in.). They generally operate at speeds sufficient to generate centrifugal forces that range from several hundred up to 3,000 *g*'s. They handle capacities from several hundred kilograms (lb) to 100 ton/hr and can handle hydraulic flows from several *L*/min (gal) up to 250 m^3/hr (1,000 gpm). These machines have been developed with many modifications to enhance their performance. One special type produced has a concurrent flow through the machine. This is often employed on waste sludges and fine materials where flocculants are generally used and can be advantageous in reducing flocculant cost and producing a better dewatered sludge.

The continuous solid bowl centrifuge basically consists of a solid-wall rotor, which may be tubular or conical in shape or a combination of the two. The rotor may rotate about a horizontal or a vertical axis because the centrifugal force is many times that of gravitational force (for many units, N_c is more than 3,000).

A typical example of this kind of equipment is a continuous horizontal centrifuge, as shown in Figure 6.7. It consists of a cylindrical rotor with a truncated cone-shaped end and an internal screw conveyor rotating together. The screw conveyor often rotates at a rate of 1 or 2 rmp below the rotor's rate of rotation. The suspension enters the bowl axially through the

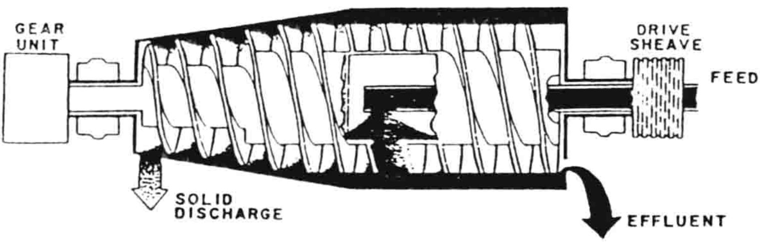

FIGURE 6.7. A continuous solid bowl centrifuge.

feed tube to a feed accelerated zone, then passes through a feed port in the conveyor hub into the pond. The suspension is subjected to centrifugal force and thrown against the bowl wall where the solids are separated. The clarified suspension moves toward the broad part of the bowl to be discharged through a port.

The solid particles being scraped by the screw conveyor are carried in the opposite direction (to the small end of the bowl) across discharge ports, through which they are ejected continuously by centrifugal force.

As in any sedimentation centrifuge, the separation takes place in two stages: settling (Figure 6.4, in the right part of the bowl) and thickening or pressing out of the sediment (left-hand side of the bowl). Because the radius of the solid discharge port is usually less than the radius of the liquid overflow at the broader end of the bowl, part of the settled solids is submerged in the pond. The remainer, closer to the center, is inside the free liquid interface, where they can drain before being discharged. The total length of the "settling" and "pressing out" zones depends on the dimensions of the rotor. Their relative length can be varied by changing the pond level through suitable adjustment of the liquid discharge radius. When the pond depth is lowered, the length of the pressing out zone increases with some sacrifice in the clarification effectiveness.

The critical point in the transport of solids to the bowl wall is their transition across the free liquid interface, where the buoyancy effect of the continuous phase is lost. At this point, soft amorphous solids tend to flow back into the pond instead of discharging. This tendency can be overcome by raising the pond level so that its radius is equal to, or less than, that of the solids discharge port. In reality, there are no dry settled solids. The solids form a dam, which prevents the liquid from overflowing. The transfer of solids becomes possible because of the difference between the rotational speed of the screw conveyor and that of the bowl shell. The flights of the screw move through the settled solids and cause the solids to advance. To achieve this motion, it is necesary to have a high circumferential coefficient of friction on the solid particles with respect to the bowl shell and a low coefficient axially with respect to the bowl shell and across the conveyor flights. These criteria may be achieved by constructing the shell with conical grooves or ribs and by polishing the conveyor flights. The conveyor or differential speed is normally in the range of 0.8%–5% of the bowl's rotational speed.

The required differential is achieved by a two-stage planetary gear box. The gear box housing carrying two ring gears is fixed to, and rotates with, the bowl shell. The first stage pinion is located on a shaft that projects outward from the housing. This arrangement provides a signal that is proportional to the torque imposed by the conveyor. If the shaft is held rotational (for example, by a torque overload release device or a shear pin), the relative conveyor speed is equivalent to the bowl rotative speed divided by the gear box ratio. Variable differential speeds can be obtained by driving the pinion shaft with an auxiliary power supply or by allowing it to slip forward against a controlled breaking action. Both arrangements are employed when processing soft solids or when maximum retention times are needed on the pressing out zone. The solids handling capacity of this type centrifuge is established by the diameter of the bowl, the conveyor's pitch, and its differential speed.

Feed ports should be located as far from the effluent discharge as possible to maximize the effective clarifying length. Note that the feed must be introduced into the pond to minimize disturbance and resuspension of the previously sedimented solids. As a general rule, the preferred feed location is near the intercept of the conical and cylindrical portions of the bowl shell. The angle of the sedimentation section, with respect to the axis of rotation, is typically in the range of 3 to 15°. A shallow angle provides a longer sedimentation area with a sacrifice in the effective length for clarification. In some designs, a portion of the conveyor flights in the sedimentation area is shrouded (as with a cone) to prevent intermixing of the sedimented solids with the free supernatant liquid in the pond through which they normally would pass.

In other designs, the clarified liquid is discharged from the front end via a centrifugal pump or an adjustable skimmer that sometimes is used to control the pond level in the bowl. Some displacement of the adhering virgin liquor can be accomplished by washing the solids retained on the settled layer, particularly if the solids have a high degree of permeability. Washing efficiency ranges up to 90% displacement of virgin liquor on coarse solids.

The longer section of a dry shallow layer provides more time for drainage of the washed solids. This system is especially effective for washing and dewatering such spherical particles as polystyrene. In either washing system, the wash liquid that is not carried out with the solids fraction returns to the pond and eventually discharges along with the effluent virgin liquor.

Screen Bowl Centrifuge

Another version of this machine is called the screen bowl. The construction is generally similar to that of the solid bowl, except that, after the solids have been removed from the pool, a screen section is employed where further washing and dewatering can take place. This, in effect, makes this a combination sedimentation and filtering centrifuge. It provides the advantage of both types of equipment. As mentioned under filtering centrifuges, the performance generally increases as the solids concentration is increased. In the screen bowl centrifuge, the discharge of a solid bowl is delivered to the screen portion. This provides for maximum dewatering with minimum retention time on the screen; it also minimizes solids losses through the screen. The benefits of additional dewatering and improved washing are achieved in the screen section of the centrifuge.

Disc Centrifuges

Another style of the basic sedimentation centrifuge is the high-speed, disc centrifuge. These were ordinarily designed as cream separators, but, through the years they have been developed to a high degree of sophistication and have found many applications in the process industries. They are used for liquid-liquid separations, solid-liquid separations, and liquid-liquid-solid separations. Disc-type centrifuges are used to separate and concentrate solids from slurries where the particle size is finer than 200 mesh down to submicron material. Only a very small-density difference is required to separate solids in these high *g* machines. If oversized material is present, screens or other devices are used to remove oversized materials that might plug discs or nozzles in the machine. These centrifuges are generally built in sizes ranging from 200–1,000 mm (8–40 in.) in diameter. They have capacities varying from 200 *L*/min (0.1 gpm) up to 230 m^3/hr (1,000 gpm).

The disc-type centrifuge is built in several different types of bowls and discharge arrangements. The conventional liquid-liquid separator has no automatic sludge discharging means and must be disassembled for sludge removal; thus, it is used only where the smallest amounts of solid phase material are anticipated.

The "self-opening"- or "desludging"-type nozzle centrifuges are built with a reservoir to hold solids. Periodically, the bowl halves split to discharge the accumulated solids. This discharge can be controlled by a timer or by other controls triggered by the sludge volume accumulation in the bowl or clarity of the overflow. These machines can store up to 30 L of sludge and are used on slurries in the range of 1–10% solids by volume at feed rates up to 50 m^3/hr (220 gpm). A typical desludging-type centrifuge is shown in Figure 6.8. The arrangement illustrated is with a turbidimeter on the effluent to trigger the desludging cycle.

The nozzle centrifuge is another type of disc centrifuge. The feed enters the feed well of the high-speed rotor through a central passage. From the feed well, slurry enters the feed impeller, where it is brought up to rotor speed. Slurry then enters the separation chamber where centrifugal forces, thousands of times higher than gravity, cause the bulk of the solids to settle

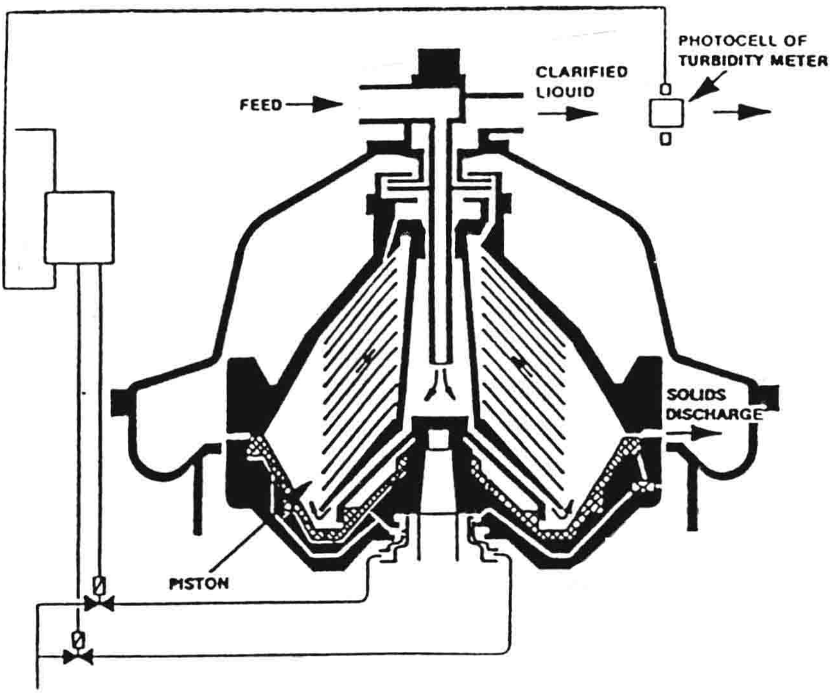

FIGURE 6.8. Desludging centrifuge: the feed is delivered into the spinning bowl where the liquid to be processed enters a set of closely spaced conical discs; here it is distributed into thin layers enhancing the action of centrifugal force. The solids are forced against the underside of each disc and slide into the sediment holding space of the bowl. When sufficient solids have accumulated, a hydraulically operated piston is activated to open ports in the periphery, and the solids are rejected through the ports by centrifugal force. Opening and closing of the bowl are accomplished while it continues to run at full speed.

to the periphery of the rotor where they are continuously expelled through fixed open nozzles in the rotor to the underflow volute. Small quantities of lighter solid material, entrained in relatively clear liquid, are forced inwardly up the disc stack, where even the smallest particles become impinged on the underside of the discs. As the solids agglomerate and gain density, they fall, counter to the liquid flow, into the separation chamber to joint the heavier material and are passed through the rotor nozzles. Thoroughly clarified, clear liquid continues up through the disc stack and out of the rotor into the overflow volute.

The nozzle-type centrifuge generally has a higher-handling capacity than the self-opening–type machine. However, the self-opening–or desludging-type machine will produce a sludge of a higher solids concentration than that which can be obtained in the nozzle type. The usual operating speeds of these machines produce centrifugal forces in the range of 5,000–8,000 *g*'s, depending upon the machine size.

Disc bowl centrifuges are used widely for separating emulsions, clarifying fine suspensions, and separating immiscible liquid mixtures. More sophisticated designs can separate immiscible liquid mixtures of different specific gravities while simultaneously removing solids. Figure 6.9 illustrates the physical separation of two liquid components within a stack of discs. The light liquid phase builds up in the inner section, and the heavy phase concentrates in the outer section. The dividing line between the two is referred to as the separating zone. For the most efficient separation, this is located along the line of the rising channels, which are a series of holes in each disc, arranged so that the holes provide vertical channels through the entire disc set. These channels also provide access for the liquid mixture into the spaces between the discs.

Centrifugal force causes the two liquids to separate, and the solids move outward to the sediment-holding space. The position of the separating zone is controlled by adjusting the back pressure of the discharged liquids or by means of exchangeable ring dams.

Figure 6.10 illustrates the main features of a disc bowl centrifuge, which includes a bowl (2) with a bottom (13); a central tube (18), the lower part of

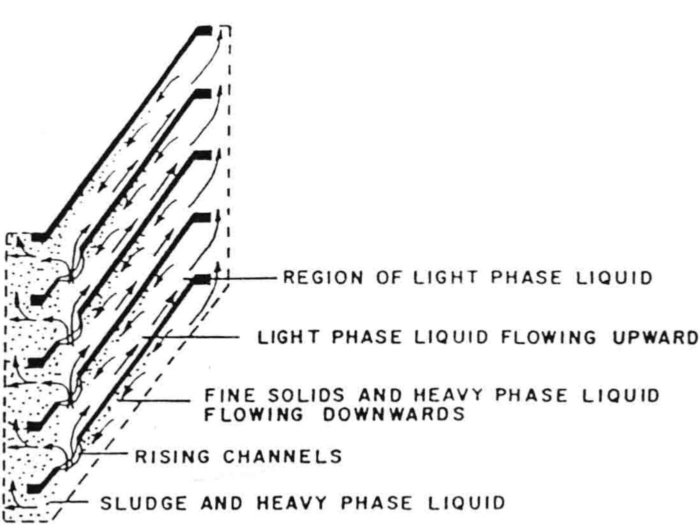

FIGURE 6.9. *The principle of separation using a stack of discs contained in a centrifuge.*

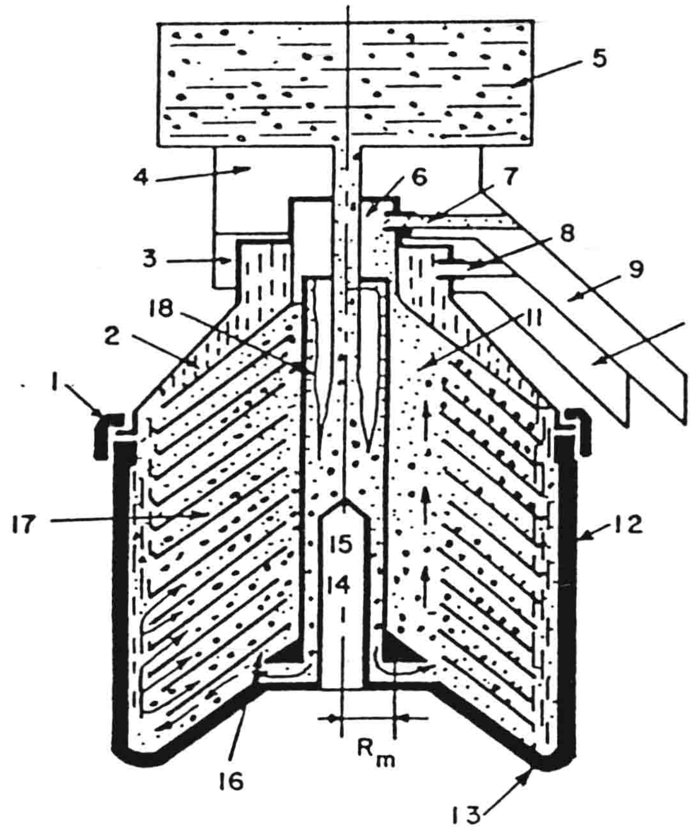

FIGURE 6.10. Schematic of a disc bowl centrifuge: (1) ring, (2) bowl, (3 and 4) collectors for products of separation, (5) feed tank, (6) tube, (7 and 8) discharge nozzles, (9 and 10) funnels for collectors, (11) through channels, (12) bowl, (13) bottom, (14) thick-walled tube, (15) hole for guide, (16) disk fixator, (17) disks, and (18) central tube.

which has a fixture (16) for discs; a stack of truncated cone discs (17), frequently flanged at the inside and outer diameters to add strength and rigidity; collectors (3 and 4) for the products of separation; and a feed tank (5) with a tube (6). The bowl is mounted to the tube (14) with a guide in the form of a horizontal pin. This arrangement allows the bowl to rotate along with the shaft.

The suspension is supplied from the feed tank (5) through the fixed tube (6) to the central tube (18), which rotates together with the bowl and allows the liquid to descend to the bottom. In the lower part of the bowl, the suspension is subjected to centrifugal force and, thus, directed toward the periphery of the bowl. The distance between adjacent discs is controlled by