Large-Scale Centrifugation

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Introduction

Industrially, centrifuges are used for a variety of purposes related to separation of materials on the basis of density. This separation usually involves separation of insoluble particulates from supernatant liquids, but can also include extraction of dissolved substances from one immiscible liquid to another of different density, separating the mixed liquids centrifugally. The blending of the liquids, transfer of the solute and separation of the immiscible phases are sequentially carried out in the same machine at high speed.

Generally, centrifuges are used throughout many manufacturing industries (**Table 1**), to separate suspended solids from liquid utilizing the centrifugal acceleration of the suspended particles directed outward from the axis of rotation. This force initiates the particle movement to the centrifuge periphery where it is trapped or contained by the wall of the rotating body. Alternatively, a density difference between two immiscible liquids is exploited to accelerate separation of the liquids (i.e. fat separation in dairies for cream or butter manufacture). A specialized use involves separation of water from fresh-cut vegetables before modified atmosphere packaging.

Much experience and information related to industrial-scale centrifugation exists within companies manufacturing the centrifugal machinery and these sources should not be overlooked when seeking information. **Table 2** lists a representative selection of companies involved in the manufacture of centrifuges and their Internet addresses current at the time of writing. The Internet itself should not be overlooked as a source of information: simply typing the word ‘centrifuges’ in the request space of one search engine provided over 25 000 items for perusal.

Centrifugation is treated as a separation unit operation in chemical engineering and the article in Dahlstrom *et al.* (1997) by Leung on centrifuges should be consulted for an engineering perspective (see Further Reading). For a comprehensive treatment of industrial centrifugation technology, Leung’s book on industrial centrifugation technology should be consulted.

Over the past 10–15 years the growing uses for centrifuges industrially has resulted in a plethora of special centrifuges designed and adapted to particular uses. However, the machines may, in general, be characterized according to the classification of **Table 3**. Centrifuges fall into two general classifications, termed sedimentation centrifuges and filter centrifuges. In sedimentation centrifuges, solids are transported to the periphery wall of the rotating machine bowl and collected against this surface; liquid is removed from the solids by the close packing of the individual particulates. In filter centrifuges the solids are transported to the surface of a filter element and the solids trapped on this filter, while the liquid drains through the particulates and exits through the filter surface. The mechanism of solids drying is thus quite different between the two types of machine and the types of material each would be expected to treat most efficiently also differ considerably. The other important parameter is whether or not the machines are fed continuously or in batch mode. Generally, batch-mode machines are often considered obsolete for large scale separations, with the important exceptions of the continuing use of batch-mode basket centrifuges for the last recovery stages for white sugar and in the fresh-cut vegetable industry. Other exceptions also exist.

The approximate capabilities of several centrifuge types are indicated in **Figure 1**. The list is not exhaustive but examples of most types of centrifuge,

Table 1 Industrial use of centrifugal technologies

Food and agri-business
Sugar crystal recovery
Dewatering of fresh-cut salad and vegetables
Milk processing, bacterial removal, cream separation
Pulp-free orange juice
Formation of fruit and vegetable juices
Frying oil clean-up

Pharmaceutical/biotechnology
Recovery of valuable isolates
Recovery of cells (yeast and bacteria, plant and animal cells)
Clarification of fermentation broths

Environmental industries
Sewage solids recovery
Wastewater treatment
Removal of metal cuttings from industrial cutting lubricants

Chemical industries
Black coal separation from slurries
Isolation of synthetic products
Gas-phase isotope separation

Table 2 Companies manufacturing centrifugal equipment which may be contacted through the Internet[a]

Alfa Laval Sharples	http://www.als.thomasregister.com
Barrett Centrifugals	http://www.barrettinc.com
Bird Machine	http://www.bakerhughes.com/bird/birdhome.htm
Carr Separations	http://www.carrsep.com
Dorr-Oliver	http://www.dorroliver.thomasregister.com
Eillert Veg. Proc. Mach.[b]	http://www.eillert.nl
Rousselet Centrifugation	http://www.rousselet.com
Tema Systems[c]	http://www.tema1-usa.com/corp.htm
Westfalia Separator	http://www.westfalia.com/default.htm

[a] The list is representative, not exhaustive. [b] Fresh cut vegetable processing. [c] Manufactures under licence from Siebtechnik (Germany).

along with an estimate of the range of **g** forces available from each machine type, is provided for purposes of illustration and estimation of requirements. Basket centrifuges are normally of low speed and provide maximum **g** forces in the 1500–2000 range.

Sedimentation Centrifuges

Centrifuges in this group (**Table 3**) collect particles against the centrifuge bowl wall. The centrifugal force exerted on a particle which causes particle movement to the wall is often expressed as the number of earth gravities (**g**) which a machine is capable of developing (**Figure 1**). Particles sediment in the centrifugal field at a rate which increases with the centrifugal speed, increased particle size, increased density difference between liquid and solid phases, increased centrifuge radius and decreased fluid viscosity. The physical size, shape, design and construction of the centrifuge, in part, determine machine performance, but other factors affecting the properties of the feedstock are also important. Good separations of solid and liquid usually equate to high sedimentation velocity since large scale separations are usually carried out in a production plant where time is important, or in continuous-flow equipment where sedimentation velocity affects throughput rates.

Table 3 Classification of centrifuges for industrial use according to general principles of operation

Sedimentation centrifuges
- Continuous feed
  - Solid bowl decanter (scroll-type centrifuge)
  - Tricanter
  - Disk centrifuges (separators)
    - Intermittent discharge
    - Nozzle discharge
  - Hydrocyclones
- Batch feed
  - Imperforate basket (generally considered obsolete, replaced by decanter)
  - Solid bowl
  - Tubular

Filter centrifuges
- Continuous feed
  - Pusher centrifuge (single- or double-stage)
  - Screen/scroll
  - Screen bowl decanter
- Batch feed
  - Vertical basket (particularly for sugar industry and fresh-cut produce)
  - Peeler

Machine performance criteria are usually dependent on the purpose of centrifugation and can be measured by the purity of the separated liquid phase or the completeness of the removal of the solid phase. Performance may also be measured by several other criteria, some of which are listed in **Table 4**. A particularly effective method of enhancing separation performance is through increasing the diameter of the particles sedimented. This can be done by careful selection of conditions or addition of coagulants or flocculants. The purpose of coagulation or flocculation is to destabilize particles, inducing them to come together and agglomerate to form larger aggregates. This can be accomplished by modifying the surface charge characteristics, by modifying the hydrophobic/hydrophilic character of the particles, or by using surfactants to reduce water-binding characteristics. Alternatively, charge repulsion by individual particles is reduced by adding polyvalent cations such as aluminium or ferric ions. The materials and methods used to effect flocculation/coagulation are listed in **Table 5**. A wide array of commercially available materials are marketed carrying a wide range of molecular sizes. The flocculant/coagulant choice can be partially made on the basis of chemical knowledge of the particles to be sedimented, but the flocculant manufacturer's recommendations should also be considered in combination with empirical screening tests. Flocculant manufacturers can be particularly useful sources of information and again the Internet should not be overlooked as a source.

Sedimentation velocity is particularly important for continuous centrifuges where rapid sedimentation increases separation efficiencies and machine capacities. Particle removal from sewage particularly makes use of flocculant technology. Flocculant usage in food-processing applications is severely restricted because of health and safety regulations, and the need to provide food to consumers as free of additives as

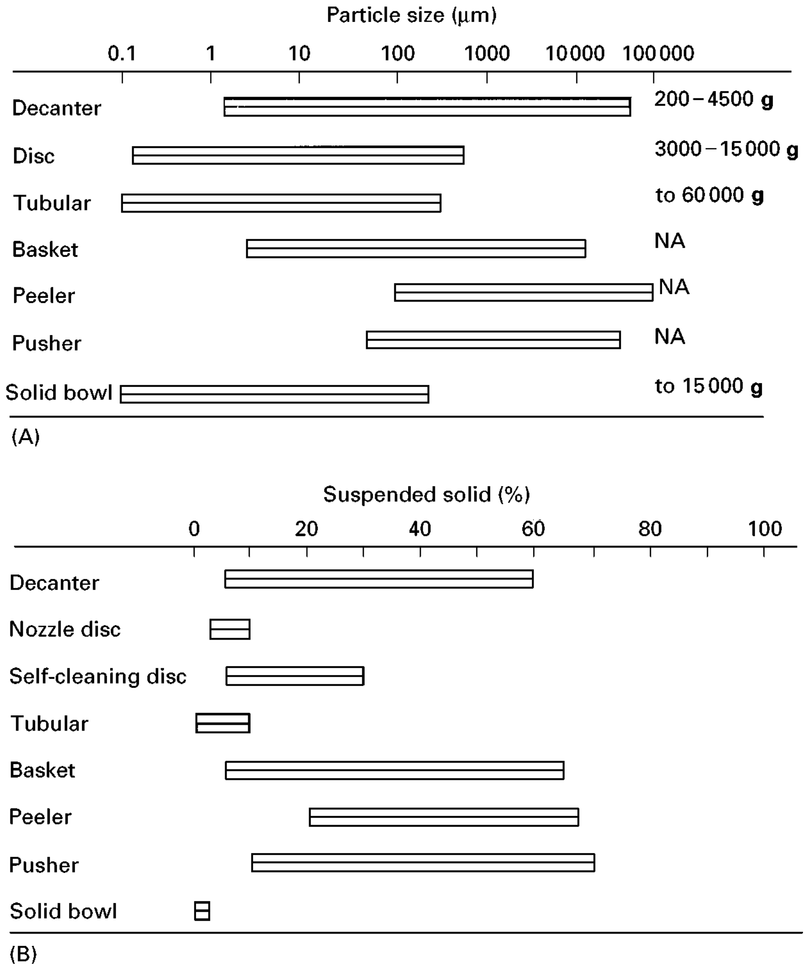

Figure 1 (A) and (B) Approximate capabilities of various centrifuge forms to sediment/separate particles and levels of suspended solids applicable. NA, Not applicable or not relevant (generally less than 1500 **g**). Adapted with permission from (http://www.temal-usa.com/centrifu.htm) and Brunner and Hemfort (1988).

possible limits the acceptable flocculants. Downstream processing of fermentation broths or biotechnologically derived natural products for removal of particulate from a liquid stream provides another application of these flocculant materials. When used prior to unit operations such as chromatography or adsorption, these materials can help provide a clean, particle-free feed which will not block the columns and adsorbent beds used for these purposes. Increasing the density difference between the liquid and solid phases is possible in certain applications by dilution prior to centrifugation if this is compatible with subsequent manufacturing steps, or by treatment with enzymes to hydrolyse viscous polymers and create denser core particles, which are more easily deposited. Apple juice manufacture by centrifugal means makes use of this latter mechanism. In this case, particle density is increased and the viscosity of the suspending liquid is reduced, both facilitating particle sedimentation. Another way of reducing the viscosity of the suspending liquid is to increase temperature. Increasing temperature decreases viscosity exponentially, improving sedimentation rates, thus sedimentation should be carried out at the highest temperatures compatible with preservation of any desirable properties of the material separated (supernatant or particulate), and the economics of the process being considered.

Table 4 Selected performance criteria for centrifuges according to functional definitions

Cake dryness or cake moisture content
Total solids recovery
Polymer dosage (flocculent concentration)
Yield
Volumetric or solids throughput
Purity of isolate of interest (either fluid stream or solids discharged)
Power consumption
Maintenance requirement

Table 5 Coagulants and flocculants. Adjustment of conditions or addition of specific chemicals achieves required increase in particle size

- Metal salts, especially of aluminium or ferric iron ($Al_2(SO_4)\bullet 16H_2O$; $Fe_2(SO_4)_3\bullet 9H_2O$)
- Natural flocculants
  - Starch
  - Gums
  - Tannin
  - Alginic acid
  - Sugar/sugar acid polymers
  - Polyglucosamine (chitosan)
- Synthetic flocculants
  - Polyacrylamides
  - Polyamines/imines
  - Cellulose derivatives (e.g. carboxymethyl cellulose)
  - Polydiallydimethyl ammonium chloride
- Chilling temperatures below 20°C, particularly yeast cells
- pH adjustment in range 3–6
- Concentration – increases particle concentration, increasing collision frequency

Adapted from Whittington (1990) with permission.

Decanter Centrifuges

A schematic diagram of a solid bowl decanter is shown in **Figure 2**. The machine consists of a horizontally oriented cylindrical bowl with one end tapered to form a cone. Within this cylindrical/conical section is a conveying scroll, with the same profile as the cylindrical/conical bowl. This scroll is rotated at a slightly different speed from the bowl through a gear system or via a separate drive. This arrangement fixes the differential speed, allows adjustment during operation, or accommodates automatic systems. Either method ensures that the scroll turns fast enough to avoid blockage by the solids which accumulate on the scroll faces, while allowing maximum solids retention times for good separations and dry ejecta. An automatic system allows the scroll speed to be adjusted to optimize the differential speeds under operating conditions. The length of the cylindrical and conical sections and the conical angle may be varied, as can the scroll design, to accommodate diverse requirements of feedstock to achieve solids separations. Slurry to be separated is fed continuously through the centre pipe to be distributed evenly near the level of the conical taper and is accelerated to bowl speed. During acceleration, high shear forces are generated and this may result in considerable foam generation in some slurries such as food materials which contain protein or pectin capable of retaining air in suspension.

The depth of the liquid pool rotating against the bowl wall is determined by the positioning of the fluid discharge ports, dams or pick-up tubes. Solids settle through this pool to the bowl wall and are conveyed to the outlet ports at the distal conical end where they are ejected. The solids undergo a drying effect as they are dragged along the bowl wall and elevated to the exit ports as liquid drains back to the pool. Given the decanter configuration, there are four parameters which can be varied: scroll/bowl differential speed, pool depth, bowl rotational speed and feed rate. Fluid or supernatant is conveyed countercurrent to the solids, following the path of the scroll flights, to exit at a discharge port at the end of the cylindrical section. Centrifugal force can vary to over 4000 **g** depending on application and centrifuge.

The decanter's particular advantage is that it provides continuous separation of a wide variety of feedstocks with a broad range of solids concentrations. It is possible to configure a decanter to process feedstocks containing an aqueous phase, on oil phase and suspended solids, separating the three phases in the same machine. These machines are sometimes termed tricanter (**Table 3**) because of the three phase separations possible. Thus the decanter can be used to separate solid–liquid two-phase systems or solid–aqueous–oily three-phase systems. Separation

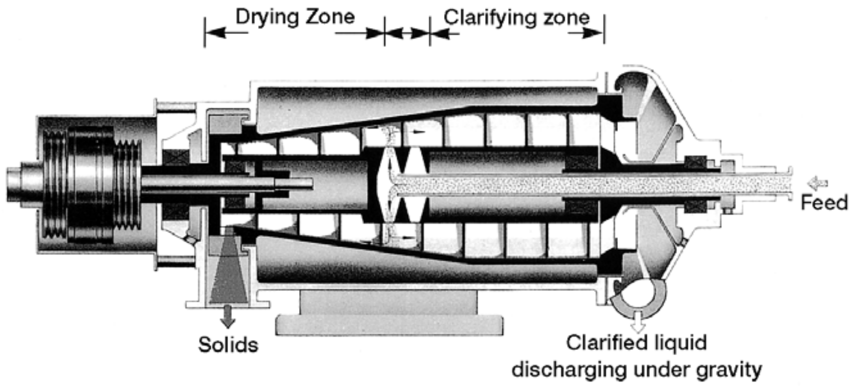

Figure 2 Schematic diagram of a decanter (scroll-bowl) centrifuge showing the major parts and indicating mode of operation. Reproduced with permission from Westfalia Separator AG, Oelde, Germany.

of two immiscible liquid phases is possible but is normally done in a disc-stack centrifuge specially designed for this purpose (i.e. cream separator). In the solid–liquid mode of operation, the ability to handle high solids content feed streams continuously, effectively and efficiently has made dewatering of municipal and industrial sewage a major use for decanter centrifuges. For similar reasons these machines have been used extensively for dewatering fine coal and for separation of mineral slurries in the mining and mineral-processing industries.

Decanters capable of separating three phases have been used to refine vegetable oils from complex feedstocks such as coconut, producing fat, milk and grated coconut solid fractions, recovery or animal fat from rendering operations and recovery of waste oil in petroleum refining. Watery oil derived from tank bottoms or trapped in containment lagoons which contain suspended solids may have this oil recovered using these machines. In each case value is added through the recovery of the oil phase as a saleable product. More recently, two-phase decanters have been adapted to replace presses in the extraction and further processing of a wide variety of fruit and vegetable juices. Separation in a tricanter of commercially exotic fruits such as sea buckthorn into pulp oil, juice and seed-enriched solid ejecta provides a potential future use of centrifugal technology. New, innovative uses for this versatile machine are still emerging.

The disadvantage of the machine is its inability to clarify liquid streams completely, as some suspended solids remain in the emerging stream. If complete clarity is required, another clarifying method must be used following decanter centrifugation. This may include equipment such as a disc centrifuge (clarifier) or filter system. For example, processes described for the extraction of fruit juices with a decanter replacing the press often have a clarifying disc stack centrifuge in the line following the decanter to provide the final solids removal and provide the brilliant clarity desired in many juice products. Alternatively, the clarifying centrifuge can be operated in such a way as to remove the particles larger than 0.5 μm diameter to provide a stable juice opalescence.

Disc Stack Centrifuges

Originally designed as cream separators, these machines have achieved a high degree of sophistication and today represent a versatile group of centrifuges capable of achieving very high **g** factors, commonly ranging from 3000 to 15 000. The original application of cream separation is still performed as a specialized function in dairies where these machines are also used for milk clarification and bacterial removal prior to high temperature–short time pasteurization. The disc stack centrifuge is a vertical-axis machine consisting of a series of conical spacers stacked within the centrifuge rotor (**Figure 3**). The centrifuge is arranged to allow continuous flow of feedstock into the lower part of the bowl. Fluid flows up through the channels formed by the stacked conical elements and particulates are sedimented to contact the inclined surface of a conical element. The particulates on the conical element are forced downward and outward until they underflow the cone to collect on the bowl wall. The effect of the angled conical element is to shorten the distance required for particle migration to a surface and reduce the turbulence produced by material flows within the centrifuge, resulting in rapid and complete clarification of the fluid stream. The number and spacing of the conical elements are important factors in the separation process.

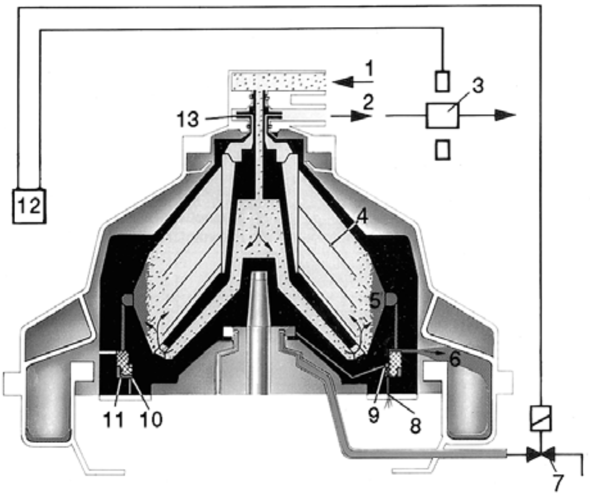

Figure 3 Bowl section of a self-cleaning disc stack centrifuge indicating direction of fluid flow and ejection of sedimented solids through passages controlled with hydraulically operated pistons. Discharge is intermittent. Nozzle machines allow for continuous discharge of solids through throttled nozzles while solid bowl machines without solid discharge mechanisms require manual cleaning from time to time depending upon feedstock solids. 1, Feed; 2, discharge; 3, photocell; 4, discs; 5, sediment holding space; 6, solids ejection ports; 7, operating water valve; 8, drain hole; 9, opening chamber, 10, closing chamber; 11, annular piston; 12, timing unit; 13, discharge pump. Reproduced with permission from Westfalia Separator AG, Oelde, Germany.

These centrifuge types are for processing feedstocks with relatively low suspended solids in a feedstock requiring a high degree of clarification. They are also of use in situations requiring separation of two immiscible liquids – the separation of cream from milk is the most common example. However, extraction of biochemicals from aqueous substrates often makes use of water-immiscible organic solvents and rapid separation of the two phases can be achieved in these machines. Removal/isolation of culture-grown bacterial or other cell is a useful function in the biochemical industries. In any role, consideration should be given to the need to seal the centrifuge against the dispersion of aerosols which may contain dangerous biochemicals, nonaqueous vapours or bacterial cells which may be toxic, flammable or explosive. Flushing with an inert gas such as nitrogen or carbon dioxide to avoid oxidation, and the need for temperature control of the centrifuge, feedstock and products should also be considered.

Disc stack centrifuges come in three basic configurations. In one configuration the sedimented solids are continuously ejected through carefully sized nozzles at the bowl periphery (nozzle discharge), allowing continuous operation of the machine with continuous discharge of solids. However, the degree of compaction of the solids is limited by the need to be free-flowing, and solids exit as a concentrate (~ 50%). In the second configuration, the bowl is equipped with the means to open a port at the periphery of the rotating bowl. This opening may be closed with a slide or piston which is hydraulically opened according to a pre-set programme. The programme may be set by time or the centrifuge may be equipped with a monitoring device on the fluid exit side which monitors the light-scattering capability of the clarified output. Above set limits clarity deterioration triggers solid discharge. The centrifuge illustrated in Figure 3 is of this self-cleaning type. The third configuration is a solid-wall bowl which is primarily used for separation of liquid mixtures containing little or no solids. The bowl is cleaned manually, or with automatic removal machinery which requires process interruption, so it is advantageous for the sedimented solids content to be low since the machine operates in batch mode and machine capacity will be a function of the clean-out rate.

Solid Bowl and Tubular Centrifuges

Other batch-operated sedimenting centrifuges are the tubular centrifuge and the solid open-bowl centrifuge (without discs: Table 3 and **Figure 4**). Both machines are batch-operated because they do not incorporate the means for continually removing sedimented solids. The tubular centrifuge is configured with a long, small diameter tube capable of rapid rotation

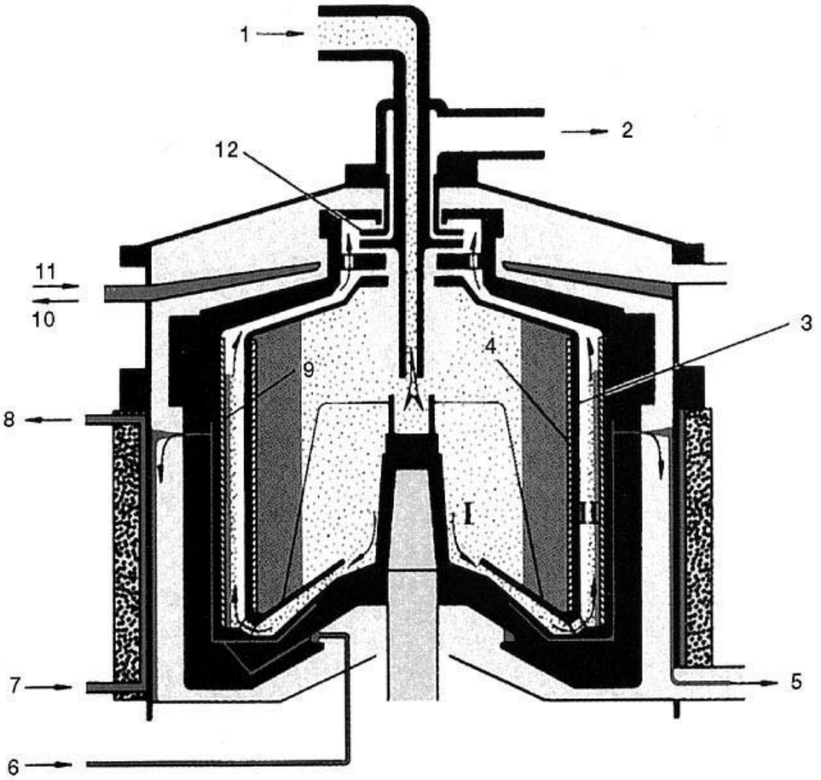

Figure 4 Solid-bowl separator for separating and collecting fine suspended solids in a liquid stream. 1, Product feed; 2, product discharge; 3, bowl insert; 4, removable liner; 5, coolant discharge (bowl); 6, coolant feed (bowl); 7, coolant feed and 8, coolant discharge (upper section of frame); 9, removable liner; 10, coolant discharge and 11, coolant feed (hood); 12, centripetal pump. Reproduced with permission from Westfalia Separator AG, Oelde, Germany.

and generating very high **g** forces to above 40 000 **g**, whereas the solid-bowl/chamber-bowl machines carry a larger diameter bowl and operate in the 5000–10 000 **g** range. The solid-bowl machines are often equipped with a removable liner to facilitate solid removal and centrifuge cleaning, to reduce down time between batches. The narrow tube means that the solid-retaining capacity of the tubular centrifuge is small but the high **g** force makes the machine useful for collecting small particulate or cell debris in biotechnological applications. They are particularly useful for collecting a valuable particulate present at low concentration which requires high relative centrifugal forces for its isolation. Final cleaning of a fluid stream is another application, particularly for the solid-bowl machine, if the solid to be removed is of a refractory type, which would impose extensive wear on the nozzles or solid ejection ports of a disc stack machine or where high compaction of the solids is of value. This latter condition can be very desirable for biotechnological applications where isolation of expensive precipitates is a key function.

Hydrocyclones

This device is particularly unique as it separates solids and liquids by centrifugal principles, but contains no moving parts. The principle of the machine is illustrated in **Figure 5**. The slurry or fluid to be separated is pumped at high speed and enters the conically shaped machine tangentially. The conical shape causes the flowing liquid to swirl or rotate within the cone, with the result that suspended solids move to the wall while clarified liquid remains in the centre of the cone. This clarified liquid is drawn off at the top of the cone while the separated solids move to the bottom of the chamber for removal. The degree of separation is generally coarse; however, hydrocyclones find use in applications such as removal of sand or grit from fruit mash streams intended for juice extraction, to protect expensive equipment such as decanter scrolls or disc stack deslugging mechanisms from premature wear. They find use in pulp mills for paper fibre removal from liquid streams. These units are used extensively to remove particles from gas streams such as flue gases and as a particle collection mechanism for spray driers used in the production of food powders of various kinds. While the medium of drying and particle conveyance is air, and the prefix 'hydro' does not strictly apply, the principle is the same. Hydrocyclones may precede in line with filtering centrifuges since they can be used to concentrate the centrifuge feed and increase the efficiency of the basket or filter centrifuge.

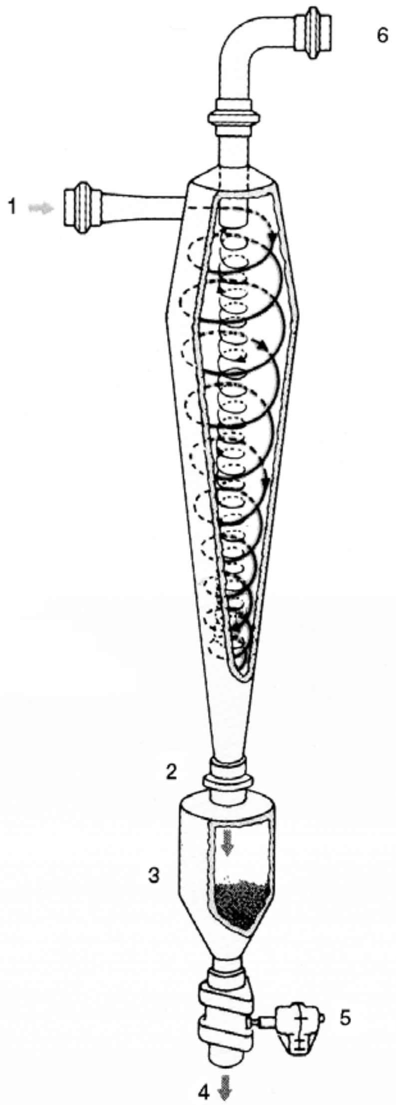

Figure 5 Schematic diagram of a hydrocyclone. 1, Feed; 2, apex nozzle; 3, grit pot; 4, outlet, solids; 5, valve; 6, discharge, clarified liquid. Reproduced with permission from Westfalia Separator AG, Oelde, Germany.

Filter Centrifuges

These machines are characterized by sedimenting particulate on to a screen which may consist of slots, holes, a porous membrane, or filter cloth, where the solids are retained while the liquid portion flows through the screen to be carried away (**Figure 6**). Generally, the solids should be free-draining and at least 100–200 μm in diameter. These properties allow filter centrifuges to handle high solid concentrations in the input stream (Figure 1b: basket, peeler, pusher). It is of advantage to feed the machine with a feedstock of high solid concentration, since this promotes frequent machine cycling. Solid concentrations can be enhanced by using hydrocyclones or

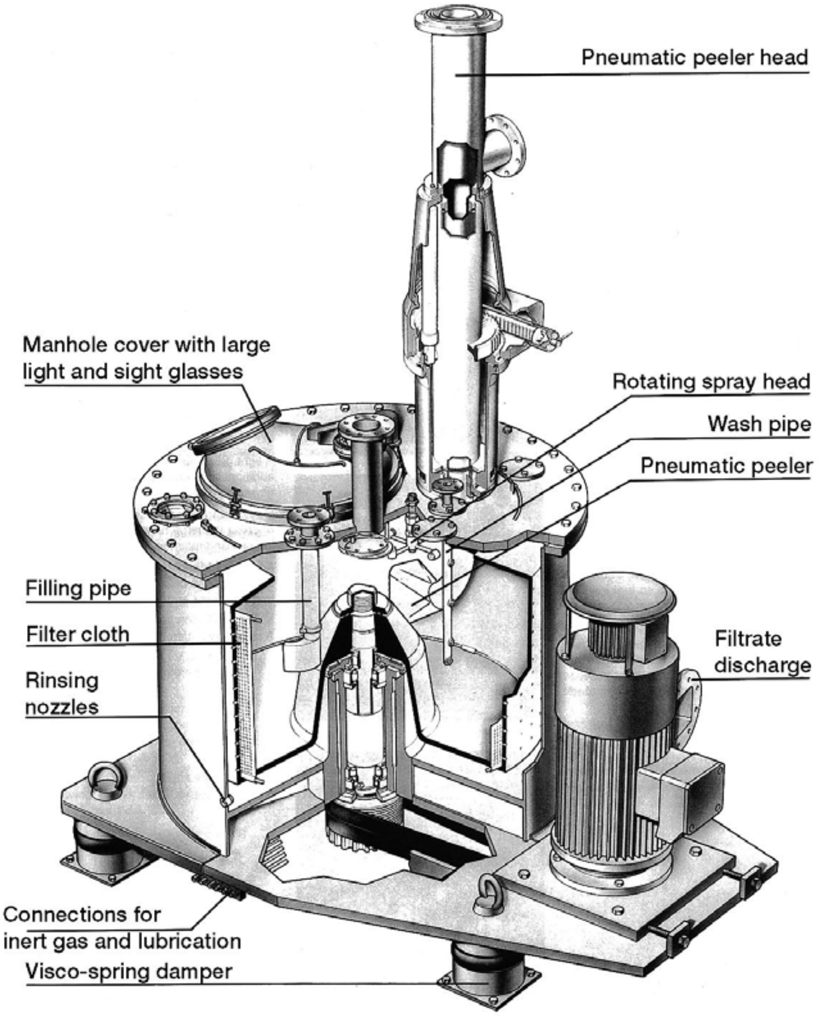

Figure 6 Vertical basket centrifuge with pneumatic top discharge. Reproduced with permission from Krauss Mofferi, Munich, Germany.

settling tanks as pretreatment concentrators. The revolving bowl may be driven either from above or below the rotating parts. The cycle of a variable-speed basket centrifuge consists of acceleration to medium speed, slurry feed and even distribution over the retaining filter surface, and acceleration to operational speed to remove the liquid portion. At this higher speed the dewatered cake may be washed if the centrifuge is equipped with interior washing nozzles, and dewatered for the final time. The rotor speed is decreased and the solids removed, usually by mechanical means using a knife or plow to release the cake from the centrifuge wall. Solids are either dropped through the centrifuge bottom in a vertical axis machine, or gravity-fed down a chute in a horizontally mounted machine. Batch machines offer flexibility in centrifugal conditions, allowing adjustments for feed rates or feed solid concentration; however, they are not widely used except in the white sugar industry since the higher throughput capacity makes continuous centrifuges more attractive.

Basket centrifuges can be made continuous by incorporating the means of removal of solids while the machine operates. Machines mounted horizontally utilizing a knife to peel the solids from within the centrifuge bowl are termed Peeler-type basket centrifuges (**Table 3**). In this configuration the knife enters the centrifuge and unloads the cake while the machine operates at full speed. This overcomes the requirement for speed management and permits shorter cycles and higher throughput capacities than simpler batch basket centrifuges. Vertical pneumatic conveying (**Figure 6**) is another possibility. Pusher centrifuges also fulfil this requirement for continuous operation. A double-stage pusher centrifuge is shown in **Figure 7**. Multiple-stage machines are available.

The centrifuge consists of a rotating perforated basket with an open end. Feed is through a rotating

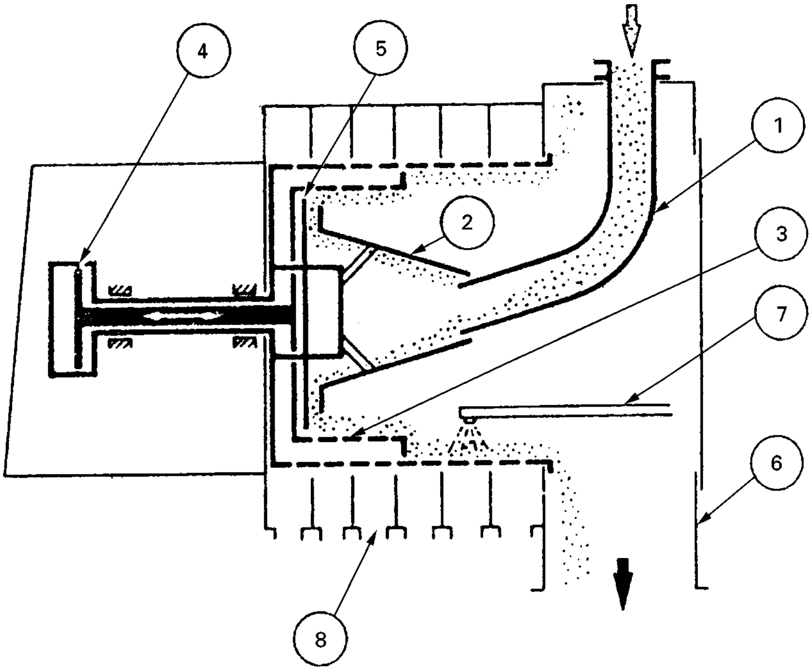

Figure 7 A two-stage pusher-type centrifuge. Feed enters at (1) and is accelerated while passing over the cone (2) and distributed on the first-stage basket (3). The first-stage basket (4) hydraulically reciprocates under a static pusher plate (5), which advances the filter cake to the second-stage basket on the back stroke. The forward stroke of the first basket pushes the second basket cake off into the collecting chute (6). The means to wash the filter cake (7) and collect mother liquor or wash fluids (8) is usually provided. Reproduced with permission from White (1979).

hollow tube to a solid distribution device which distributes the slurry evenly on the basket during the back stroke of the hydraulically driven distributing plate. On the forward stroke the distributing plate exerts a pressure on the deposited cake, causing it to overflow the open end of the basket. If required, the deposited cake may be washed before the return stroke causes overflow of the solids. The screen/scroll centrifuge is also horizontally oriented, but the basket is conical-shaped and transport of the deposited, centrifugally dried slurry is accomplished by a scroll or scrapper blades in a manner reminiscent of the decanter scroll. The transported solids overflow the open end of the basket and are removed from the machine. The screen-bowl decanter is of similar design to the solid-bowl decanter discussed earlier except for the addition of a cylindrical screen behind the conical section of the bowl. The scroll spans the entire length of the bowl including the screen and conforms to the profile of the bowl and screen. Solids retained on the screen are scraped by the scroll to an exit beyond the screen. The purpose of the machine is to combine the solid sedimenting centrifuge with a screen centrifuge in an attempt to obtain a drier cake. Washing of retained solids may be effected in the first portion of the screen, while dewatering taking place in the second part. Decanters such as this may provide serious competition to the peeler and pusher centrifuges by facilitating continuous separations in a more compact, mechanically simpler package.

A special application which is of growing importance in the food industry is the use of low speed basket centrifuges to dewater or dry fresh-cut vegetables, especially salad greens, for later use in modified atmosphere packages (**Figure 8**). These machines are usually of lighter construction than the heavy-duty machines described above, are batch-operated, and often have reusable rotating perforated baskets, to facilitate rapid unloading and reloading of the centrifuge. The reusable baskets are usually of light construction, often plastic, to allow easy manual handling and economic replacement. Such materials have low tolerance for acceleration and deceleration forces but are well suited for undemanding applications.

Summary

This article has provided an overview of the use of centrifuges in various industries. The ubiquitous nature of the machine throughout the industrial spectrum is apparent. It appears in heavy industrial uses such as sugar and oil refining and in light industrial

Figure 8 Small industrial-scale centrifuge for dewatering fresh-cut produce. The machine is operated in batch mode, but use of insertable plastic bowl minimizes down time between loads. Reproduced with permission from Freshline Machines, Sydney, Australia.

separations such as dewatering of vegetables. Performance demands also vary widely, ranging from high **g** applications required in isolating and manufacturing the diverse products of biotechnology to dewatering hundreds of tons of municipal sewage per day using machines of relatively low **g** capability. This is made possible by the wide variety of machines available. The recent application of decanters as press replacements in the fruit and vegetable juice industry required the independent development and widespread use of pectin-digesting enzymes (pectinases) for routine juice production. The reduction in viscosity and release of dense core particles from the fruit mash which is characteristic of the action of these enzymes is a necessary precondition for the successful use of decanters. The fruit-processing industry is increasingly interested in the production of products from new, unconventional fruits and vegetables. An example is sea buckthorn, a fruit which consists of a seed, pulp and pulp oil, a three-phase system which might be separated into an oil stream, a stable opalescent juice and a seed containing pulpy ejecta in a single operation using a three-phase decanter. From these two examples drawn from the author's experiences in this industry it appears that future innovations are likely to be applications, which will in turn drive further refinement and development of the centrifugal machinery.

See also: **II/Centrifugation:** Theory of Centrifugation.

Further Reading

Beveridge T (1997) Juice extraction from apples and other fruits and vegetables. *Critical Review of Food Science and Nutrition* 37: 449–469.

Brunner KH and Hemfort H (1988) Centrifugal separation in biotechnological processes. In: Mizrahi A (ed.) *Downstream Processes: Equipment and Techniques. Advances in Biotechnological Processes*, vol 8, pp. 1–50. New York: Alan R. Liss.

Dahlstrom DA, Bennett RC, Emmett RC *et al.* (1997) Liquid–solid operations and equipment: centrifuges. In: Perry RH, Green DW and Maloney JO (eds) *Perry's Chemical Engineers' Handbook*, 7th edn, pp. 18–106. New York, NY: McGraw-Hill.

Leung WW-F (1998) *Industrial Centrifugation Technology*. New York: McGraw-Hill.

White WF (1979) Centrifuges. In: Bhatia MV and Cheremisinoff PN (eds) *Solids Separation and Mixing*. Process Equipment Series, vol. 1, p. 81. Westport CT: Technomic.

Whittington PN (1990) Fermentation broth clarification techniques. *Applied Biochemistry and Biotechnology* 23: 91–121.

Macromolecular Interactions: Characterization by Analytical Ultracentrifugation

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Analytical ultracentrifugation refers to the analysis of a macromolecular solution by its subjection to gravitational forces up to 300 000-fold greater than gravity. From its inception by Svedberg in the mid-1920s, analytical ultracentrifugation has played a leading role in studies of macromolecular systems. One early success was its demonstration that proteins were polypeptides of discrete length rather than