CHAPTER 4.3

Fluidized-Bed Classifiers

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The current industry standard for hydraulic classifiers (or separators) is the result of a development process that started more than 40 years ago. For decades, classification was accomplished by mechanical means using rake, screw, or other similar types of classifiers. These machines dominated the industry, particularly for closed-circuit grinding applications, until the onset of classifying hydrocyclones. In parallel, a great deal of work was performed with dense flow hydraulic classifiers, both mechanical and nonmechanical. These devices were an extension of the early cone-type settling classifiers such as sand cones, desliming tanks, and launder classifiers. In these devices, the coarse particles settled into the base of the separator and were extracted via a discharge port. Dense flow separators took this process one step further with the addition of mechanical agitation of the settled solids and/or water injection into the base of the separator to improve efficiency. Examples of these early devices include the Larox cone classifier and the Lavodune classifier (Heiskanen 1993). Unit capacity, size, and weight generally led to the dominance of hydrocyclones for most classification applications, especially in closed-circuit grinding applications. However, several industries, such as fertilizer (phosphate and potash) and aggregate producers, continued to use hydraulic, or fluidized-bed, classifiers because of their very precise sizing relative to the performance of hydrocyclones.

Generally, there are two types of hydraulic classifiers: those operating in the free or partially hindered settling regime and full hindered-bed separators. The latter utilize a type of restricted discharge system in combination with a control system to regulate the exit rate of oversize particles. In both instances, the coarse solids (material larger than the target cut point for the separation) settle against a countercurrent flow of upward rising water injected near the bottom of the unit. Free-settling separators offered an advantage over earlier mechanical devices such as screw and rake classifiers as they did not require a mechanical device to assist with removal of the coarse fraction. Popular units in the 1970s and 1980s included machines such as the Lewis classifier, the Linatex S classifier, and the Krebs Whirlsizer. Although these devices were generally effective, they typically did not offer the capacity of hydrocyclones.

Eventually, better understanding of the benefits of a full hindered-bed device, along with advancements in control systems and discharge mechanisms, led to the proliferation of what is currently recognized as a modern teeter-bed separator. A teeter-bed separator is a device that restricts the discharge of the underflow stream that contains the coarse particles. The holdup of coarse particles, in combination with a rising current of fluidization water across the base of the separator, creates a teetering bed of solids where the settling characteristics of each particle are greatly affected by its proximity to other particles. In this environment, the particles are classified from top to bottom in order of increasing terminal velocity, with the fastest-settling particles migrating toward the bottom of the separation chamber. Most settling in the teeter bed is hindered, but some free settling may take place in the upper portion of the classifier. The high interstitial velocity between the suspended particles in the fluidized bed acts to reject misplaced fine particles from the high-density coarse bed, resulting in a highly efficient separation.

BASIC OPERATING PRINCIPLE

The basic arrangement of a fluidized-bed classifier is shown in Figure 1. These devices work effectively over a wide particle size range from 100 to 1,000 µm. In some extreme applications, such as sedimentary phosphate production, the upper limit may exceed 2,000 µm. These unique applications, however, require extremely high fluidization water rates. As shown in Figure 1, feed is introduced at or near the top of the separator into a free, or partially hindered, settling zone that occurs between the teeter-bed interface and the overflow of the separator. Fluidization, or teeter water, is introduced evenly across the base of the separator and flows upward to the overflow launder. The fluidized bed is formed above the point of introduction of the teeter water and extends upward into the separation chamber. The bed consists of particles with

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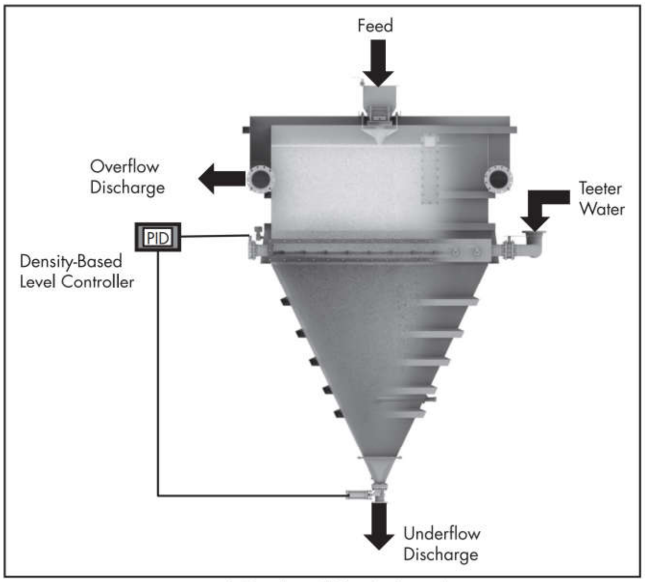


Figure 1 Conventional fluidized-bed classifier

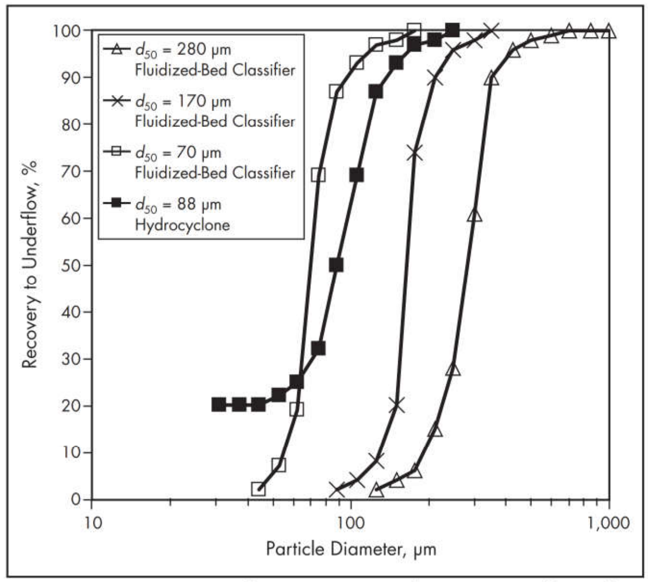


Figure 2 Comparison of separation performances achieved by a fluidized-bed classifier and a classification cyclone

a size gradation resulting from the settling velocity of the particles, with the coarsest material near the bottom and finer material toward the top of the separator. As discussed later in this chapter, the height of the fluidized bed is regulated by a control system that maintains the bed interface at a constant distance from the water injection point. Depending on the method of operation, the fluidized bed may extend to the top of the separator or be maintained at some lower point with a partial fluidized bed in the upper chamber. Fines classification takes place in the upper portion of the separator. As a result of the dense particle concentration in the fluidized bed, high fluid interstitial velocities are created. This feature serves to effectively reject finer particles from the bed. The finer material is subsequently carried to the upper portion of the separator and ultimately transferred to the overflow launder. The unique features of the fluidized bed provide a very effective means of ensuring that fine particles are not displaced to the coarse underflow fraction. As a result, unlike hydrocyclones, fluidized-bed hydraulic classifiers operate with nearly zero fines bypass.

The performance of a fluidized-bed classifier is typically defined by parameters obtained from a partition curve, which represents the recovery to the coarse product stream (typically underflow) as a function of particle size. A particle size corresponding to 50% recovery is known as the cut point (d_{50}), and the slope of the partition curve between the 25% and 75% recovery values is referred to as the imperfection value, as quantified by the following expression:

$$\text{imperfection} = (d_{75} d_{25})/(2d_{50}) \qquad \textbf{(EQ 1)}$$

where d_{75}, d_{50}, and d_{25} are defined as the particle size at each respective recovery point. A typical comparison between the classification efficiency of a fluidized-bed classifier and a hydrocyclone is depicted in Figure 2, which shows partition curves for several different cut points. Results for the fluidized-bed classifier are shown for three different applications, with the d_{50} ranging from 70 µm to nearly 300 µm. In each case, the imperfection is approximately 0.1. The hydrocyclone performance curve is less efficient, as indicated by a higher imperfection value (I = 0.27).

Another significant indicator of performance efficiency is the bypass of coarse and ultrafine particles, which can be quantified by the tails of the partition curves. Classifying cyclones are prone to bypass a significant number of ultrafine particles to the coarse product (underflow) stream because of hydraulic entrainment. For the performance comparisons in Figure 2, the hydrocyclone is bypassing 20% of the ultrafine particles entering in the feed stream to the coarse product underflow stream. The fluidized-bed classifier, by comparison, closes out at nearly zero misplacement. The high efficiency results from the deep teetering bed of coarse solids, which is continuously "washed" clean of misplaced fines by the high interstitial velocity of the fluidization water. As such, the selection of the desired classification process should consider the efficiency benefits of a fluidized-bed classifier and the generally higher unit throughput capacity per unit of floor space of a classifying cyclone. In addition, the performance of a fluidized-bed unit is relatively insensitive to changes in feed rate and solids concentration. As such, maintaining a high classification efficiency over the long term favors fluidized-bed units given that these devices provide a constant separation with little or no bypass. Additionally, in cases where a single fluidized-bed classifier can treat a given feed rate, a higher overall sizing efficiency can be achieved compared to hydrocyclones where feed is typically distributed to multiple units. Unequal feed distribution results in a flattening of the partition curve if the operating conditions and geometries of each cyclone are not identical.

THEORY OF OPERATION

Much like hydrocyclones and other classification devices, a great deal of work has been conducted over several decades to develop semi-empirical and fundamental relationships to describe settling characteristics in a hindered environment. Particle settling velocity in a pool of liquid was defined long ago by the work of Stokes and others. In hindered-bed separators, however, particle–particle interactions greatly reduce free-settling rates. The hindered effect is in response to interactions between the upward rising stream lines created by individual settling particles, an increase in the frequency of particle-to-particle collisions, and "near misses" (Littler 1986). The slower settling rate created by the hindered-settling conditions improves classification by reducing fine particle entrainment through the influence of the upward flow of fluidizing medium generated from the volume displacement created by the settling of the high population of coarse particles. According to Littler, hindered settling takes place at a volume concentration greater than approximately 20%. Several expressions have been developed to calculate the hindered-settling velocity of particles (U_t). One of the most commonly accepted expressions was developed by Masliyah (1979) and is represented as

$$U_t = \frac{gd^2(\rho_s - \rho_f)}{18\eta(1 + 0.15\,\mathrm{Re}^{0.687})}F(\phi) \quad \textbf{(EQ 2)}$$

where

g = gravitational acceleration
d = particle size
ρ_s = density of the solid particles
ρ_f = density of the fluidized suspension
η = apparent viscosity of the fluid
Re = Reynolds number

More recent modeling work by Kohmuench (2000) included the term $F(\phi)$, which corrects for the effects of particle concentration using

$$F(\phi) = (\phi_{max} - \phi)^{\beta} \quad \textbf{(EQ 3)}$$

where

ϕ = volumetric concentration of solids
ϕ_{max} = maximum volumetric packing
β = dependent on the Reynolds number (Re)

Note that Equation 3 is equivalent to the expression advocated by Richardson and Zaki (1954) when $\phi_{max} = 1$. Also, these investigators showed that
for Re < 1:

$$\beta = 4.36/\mathrm{Re}^{-0.03} \quad \textbf{(EQ 4)}$$

for Re ≥ 1:

$$\beta = 4.4/\mathrm{Re}^{0.1} \quad \textbf{(EQ 5)}$$

The Reynolds number is calculated using

$$\mathrm{Re} = \frac{d\rho_f|U_t|(\phi_{max} - \phi)}{\eta} \quad \textbf{(EQ 6)}$$

The apparent viscosity (η) in liquid-bed separations can be estimated using a semi-empirical expression suggested by Swanson (1989):

$$t\eta = \eta_w \frac{2\phi_{max} + \phi}{2(\phi_{max} - \phi)} \quad \textbf{(EQ 7)}$$

where

ϕ_{max} = highest fraction of solids by volume obtainable for a specific material having a given particle size distribution
η_w = viscosity of water or other fluidizing medium

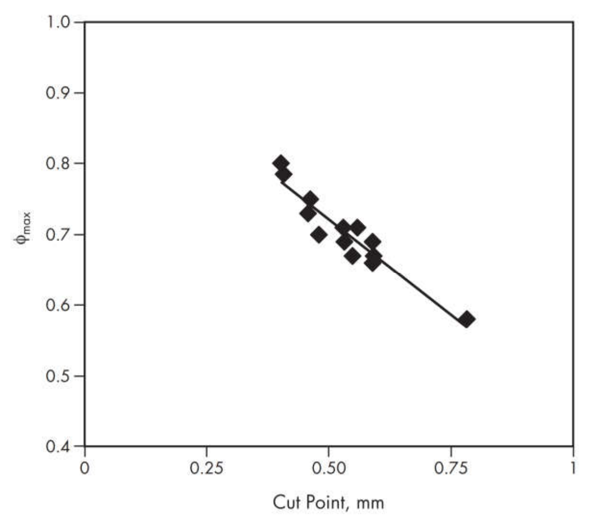


Figure 3 Effect of maximum packing fraction (ϕ_{max}) on the particle size cut point

Empirical methods are normally used to estimate ϕ_{max} (Yu and Standish 1993; Swanson 1989).

Tests conducted with the CrossFlow classifier suggested that changes to the cut point (d_{50}) had a large impact on the maximum particle concentration (ϕ_{max}) of the underflow. This effect should be expected since fine particles tend to fill voids that occur between coarser particles; however, as more fines report to the overflow, these voids remain proportionally empty. To quantify this effect, tests were conducted in which the cut point and maximum packing were determined experimentally. The test data, which are plotted in Figure 3, indicate a linear correlation between ϕ_{max} and d_{50}. A linear fit to these data yielded a coefficient of determination value (R^2) of 0.87.

Using these expressions, the overall hindered settling equation can be derived as follows:

$$U_t = \frac{gd^2(\phi_{max} - \phi)^{\beta}(\rho_s - \rho_f)}{18\eta(1 + 0.15\,\mathrm{Re}^{0.687})} \quad \textbf{(EQ 8)}$$

With this approach and because of interdependencies between the various equations, an iterative process is required to calculate the hindered settling velocity (U_t) for any particle. This approach is necessary to account for the effect of total particle concentration and other interactions on the settling rate of any single particle.

GENERAL CONFIGURATION AND OPERATION

Although there have been many designs of hydraulic classifiers over the past decades, the current generation of devices can generally be placed into one of three categories: vertical flat-bottom tank, vertical conical-bottom tank, and multicompartment type. Schematic representations of each style are shown in Figures 4A through 4C. The vertical-style separators typically have an aspect ratio greater than 1 and can be designed in a square or round configuration. Generally, past work has shown that the basic shape has no influence on the separation characteristics. Square units have the advantage of higher capacity within the same footprint, whereas round units have a slightly lower overall weight as less reinforcing

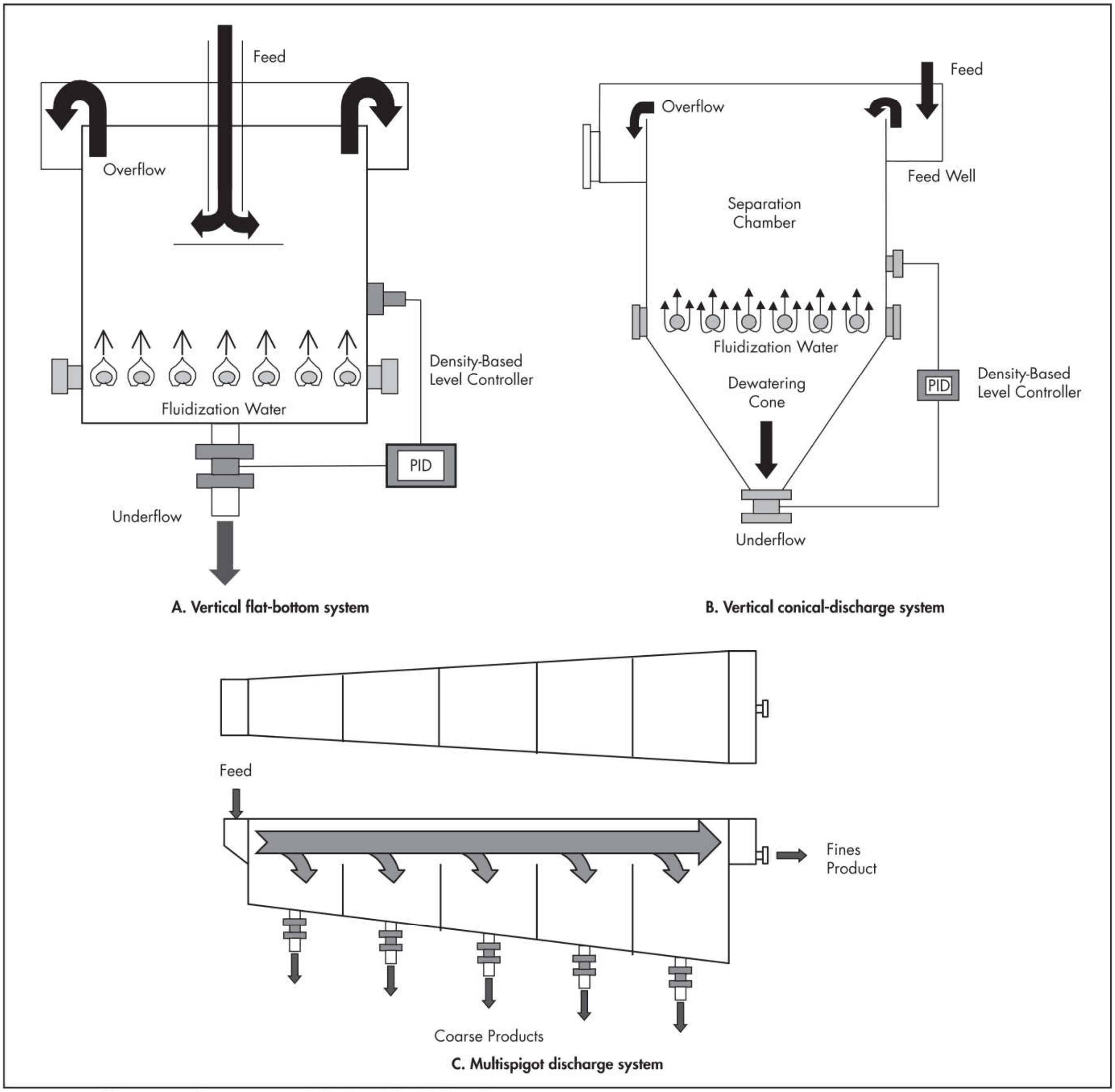


Figure 4 Different configurations of fluidized-bed classifiers

structural steel is required for the sidewalls. The multispigot design, shown in Figure 4C, has a low profile and consists of several distinct compartments along the direction of flow to provide differently sized products from the same device. They are often used for producing various grades of aggregates and foundry sands to maintain specific product criteria.

Various feed introduction designs have been promoted for vertical fluidized-bed classifiers. In general, however, the feed slurry is presented to the device in the center of the separator body and somewhat below the liquid level. A few units use tangential flow introduction to the center-well to break the slurry velocity and provide a more quiescent introduction to the separation chamber. More recently, a side-feed design has been developed that introduces the feed at the surface and to one side of the separation chamber. The intent of this design modification was to remove the bulk feed flow entirely from the separation chamber to reduce disturbances and increase overall separator efficiency by maintaining a constant upward velocity throughout the device (Kohmuench et al. 2002; Luttrell et al. 2006). The multispigot design utilizes a feedbox on one end of the device much like a bank of conventional flotation cells. The feedbox is isolated from the main separation chamber and serves to reduce disturbances and provide even feed distribution.

Feed slurry density typically ranges from 20% to 60% solids. Higher feed concentrations reduce the feed volume

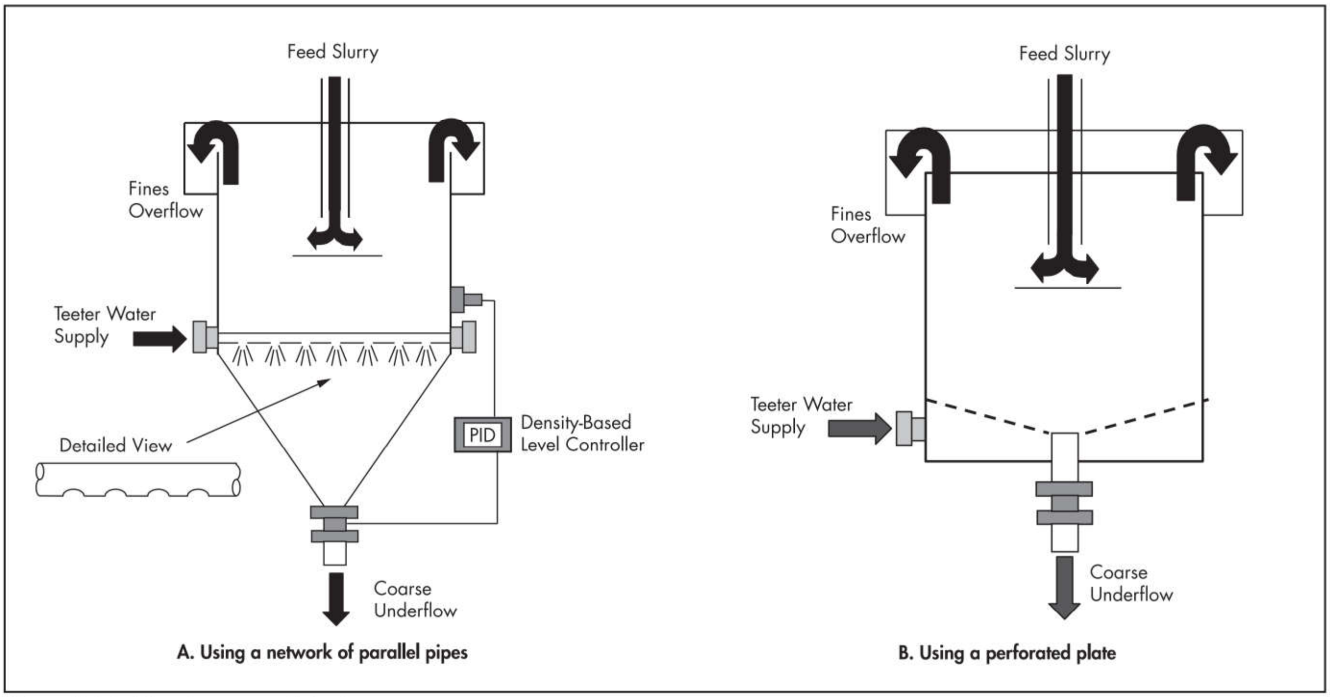


Figure 5 Fluidization water injection systems

flow rate, resulting in less disturbance to the separator. Past work has shown that, in general, the feed percent solids should not exceed the density of the fluidized bed when operating at steady state. At higher solids loading in the feed, viscosity issues can arise that will result in the feed slurry behaving as a slug, penetrating deeply into the fluidized bed, and potentially short-circuiting directly to the underflow product. Additionally, although the solids concentration (% w/w) can be relatively high when treating coarse material, the effect of fines (–0.045 mm) should be considered as their presence can greatly increase the apparent viscosity of the teeter bed and cause a decrease in particle settling rates.

Fluidization/Teeter Water

Two types of teeter water introduction systems have been used for fluidized-bed classifiers. The first, shown in Figure 5A, consists of a network of parallel pipes crossing the base of the separation chamber. The pipes terminate on both ends in water header boxes that are fed from a common supply line. Each pipe contains numerous holes that are sized to provide an even distribution of water across the length of the pipe and, subsequently, across the base of the separator. This type of water supply system offers several advantages, including the ability to remove the pipes for maintenance as well as to replace the pipes with new ones having differently sized injection holes in the event of an application change.

The second commonly used design consists of a simple perforated plate covering the base of the separator. In this design, a chamber is formed between the base of the separator and the perforated plate. Water is injected into this chamber, which acts to distribute the water evenly across the base of the separator. This approach provides a somewhat easier method to ensure equal pressure across all discharge points; however, changeover for maintenance can be more challenging. An example of this design is shown in Figure 5B.

Fluidization water is the primary operating parameter for determining the separation cut point (d_{50}). As a result, the teeter-water rate is a significant process control parameter. On the low end, the fluidization water must be sufficient to maintain the bed in a fluidized state or the device will “channel” and/or “sand out,” which is a condition that does not allow for an effective separation. Data show that there is generally a linear relationship between fluidization rate and d_{50}. This relationship is shown for two different mineral applications in Figure 6. One data set shows the effect of fluidization water rate for classification of a 1.0 × 0.106-mm phosphate matrix. In this case, a fluidization rate between 0.5 and 1.5 cm/s provided a range of cut points between 0.25 and 0.65 mm. Results for a 3.0 × 0.85-mm potash application are also shown. In this case, cut points range from 0.5 to 1.2 mm for fluidization rates of 0.75 to 2.5 cm/s.

Given a similar particle size distribution, it is expected that the denser phosphate will require a higher fluidization velocity to affect the same cut point achieved for the less dense potash (2.7 vs. 2.0 SG [specific gravity]). However, in Figure 6, there is only a moderate difference in the fluidization rate for a given cut point. This result is attributed to the influence of other process variables, mainly the feed particle size distribution and the fluidization medium characteristics. In this example, the potash is significantly coarser than the phosphate and classification is carried out using saturated brine solution as the process medium (ρ_f = 1.24 SG).

As discussed previously, mineral density also has an impact on separation performance. Cut-point predictions using fundamental particle-settling models show the effect over a range of mineral density values and fluidization rates in Figure 7. As expected, denser material requires a greater fluid rise velocity to achieve the same separation cut point since, according to Stokes’ law, settling velocity increases linearly with solid density.

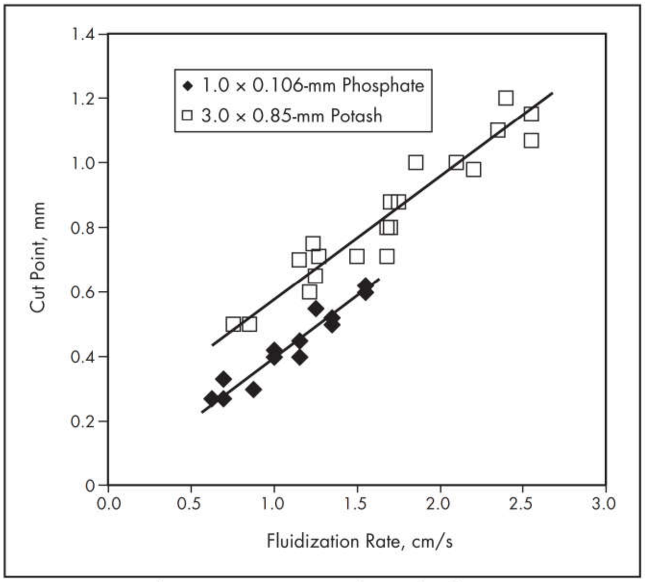


Figure 6 Particle size cut points achieved when treating phosphate and potash over a range of fluidization rates

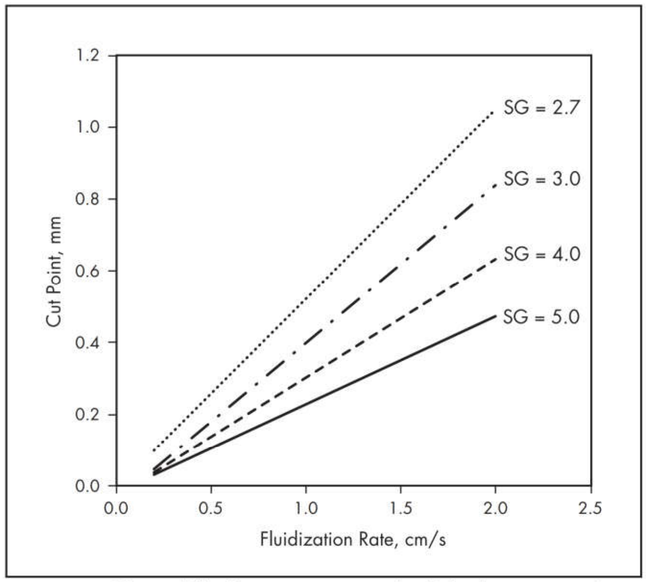


Figure 7 Effect of fluidization rate and solids density on the particle size cut point (d_{50})

Fluidized-Bed (or Teeter-Bed) Level

Unlike the fluidization rate, which expands or contracts the teeter bed, bed-level adjustment is used to modify the proportion of coarse/heavy material retained inside the separator. As such, bed level can be considered a fine-tuning parameter that modifies the height or accumulation of particles within the teeter bed and dictates the particle size that is allowed to be transported into the overflow collection launder. As more coarse material is held up within the separation chamber, the apparent weight of the suspension is increased, which elevates bed pressure. Typical response curves for separation cut point versus bed pressure are provided in Figure 8 for three different fluidization velocities. In each case, as the bed pressure increases, the separation cut point also increases. The absolute value of bed pressure depends on a specific application, separator size, and so on. However, in this case, the total range of bed pressure values shown in Figure 8 represents a physical change in bed height of approximately 30 cm.

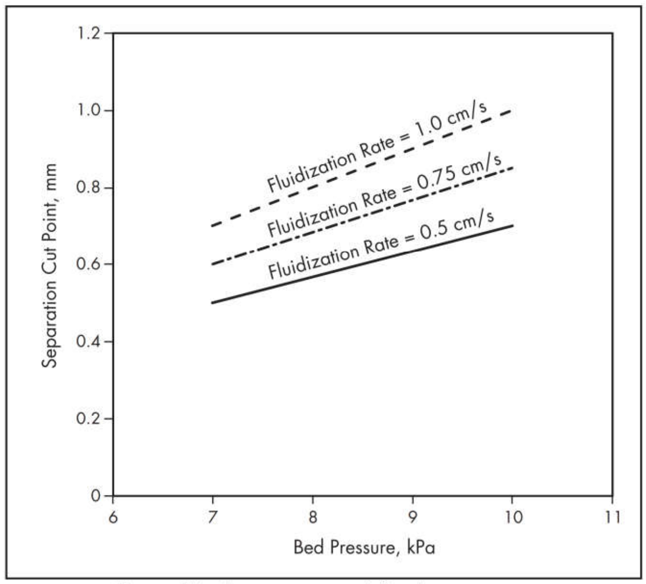


Figure 8 Effect of bed pressure and fluidization water rate on the particle size cut point (d_{50})

Control Systems

Fluidized-bed classifiers are considered operator friendly and simple to control. Traditionally, there are only two primary control variables: fluidization rate and teeter-bed level. Fluidization rate is straightforward and can be either manual or automatic. Manual control simply requires a means to measure and adjust the total volume flow rate of water entering the separator. Modern instrumentation, however, makes automation of this process variable quite simple using a flowmeter, a flow-regulating valve, and a proportional controller as shown in Figure 9. Likewise, level control is accomplished using a pressure sensor in conjunction with a proportional–integral–derivative (PID) loop controller and proportional underflow valve. The pressure sensor measures the weight of material in the separator above the sensing point, and the controller acts to maintain the bed pressure at a constant value by actuating the underflow valve. The mechanism is identical to maintaining water level in a tank or sump. In this case, however, the intent is to maintain the level of suspended solids in a pool of liquid. As such, the response is somewhat slower, requiring different setup parameters for the PID controller as compared to a typical water tank. For instance, in a cone-bottom separator, extracting material too quickly from the separator can cause "rat-holing" in the underflow, which results in short-circuiting of material from the fluidization chamber directly to the underflow, thereby negatively affecting separation efficiency. Recent modifications to the standard control system include linking fluidization water rate to differential pressure measurements as shown in Figure 10. In this instance, fluidization water rate is controlled based on readings from a differential pressure measuring system with the intent of maintaining a constant level of bed expansion (i.e., discrete bed density).

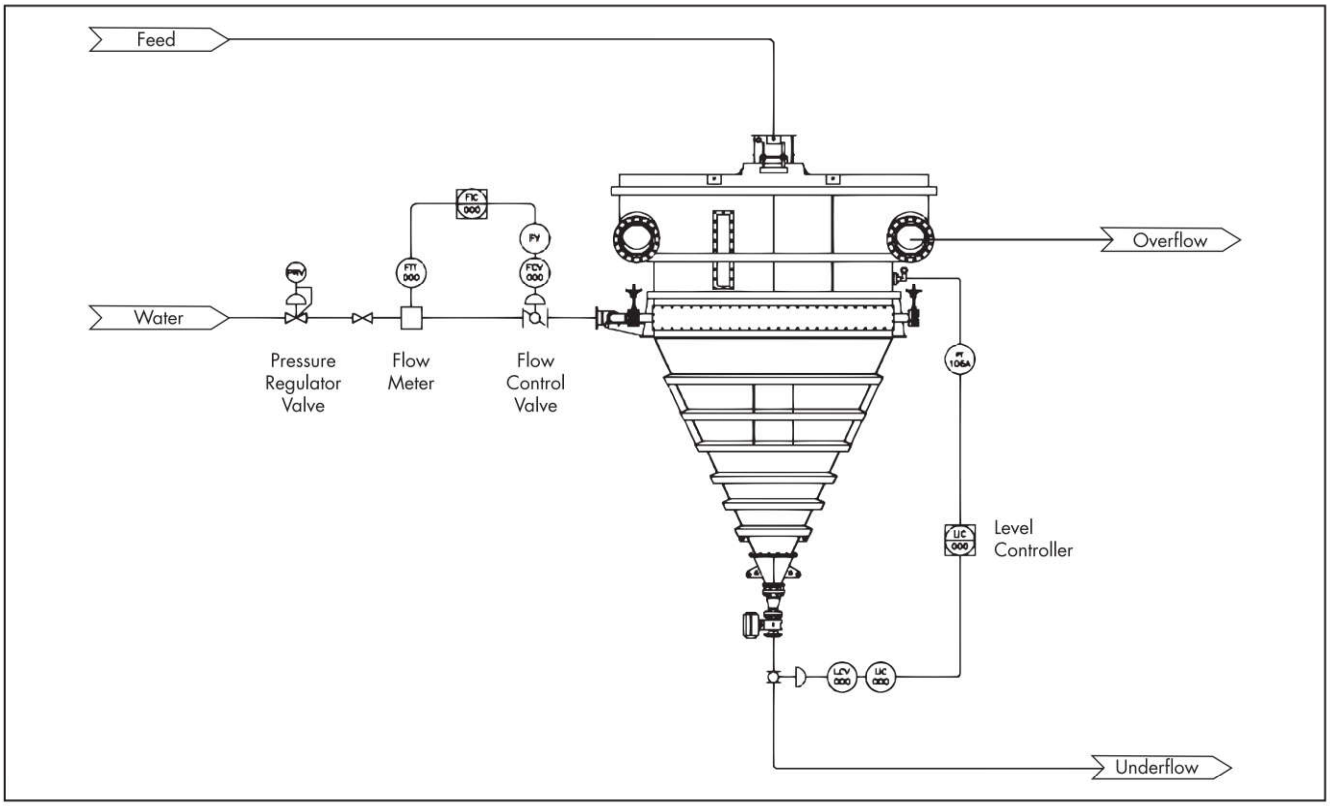


Figure 9 Typical control system used for a fluidized-bed classifier

Additionally, several flat-bottom machine manufacturers incorporate multiple underflow discharge valves. Flat-bottom designs have been developed to reduce overall separator height. In this system, the underflow discharge is drawn directly from the fluidized bed as opposed to the dewatered material in the cone. As such, multiple drawpoints are required to pull evenly from the bottom of the separator. Because of the proximity of the underflow valves to the fluidized bed, a portion of the fluidization medium can be bypassed directly to the underflow stream, which can negatively affect the upward flow rate. In these cases, the fluidization rate can be adjusted in proportion to the underflow valve position to compensate for any bypass. Additionally, each drawpoint is opened sequentially to minimize the total discharge from any one valve.

TYPICAL APPLICATIONS

Particle–particle separation achieved by a system that fluidizes particles using an upward flow of elutriation water was a common industrial operation until it was replaced by more efficient technologies. However, recent advances in control technologies have provided the ability to optimize and maintain a high level of separation performance at a relatively high mass throughput. This section reviews the applications where fluidized-bed classifiers have been installed in industrial processing facilities for treating coal and a variety of ore types.

Classification

Fluidized-bed classifiers are well-proven technologies for particle size classification. These devices offer a high-capacity alternative to hydrocyclones while providing an extremely efficient separation over a wide particle size range from 100 to 1,000 µm. The units are particularly effective at rejecting ultrafine material (Figure 2) while also removing deleterious low-specific-gravity materials such as plastic, wood fiber, and organic contaminants. Additionally, the machines can be gravity fed, have no moving parts, and require no energy input, except for the energy required to pressurize the fluidization water and operate the control system. As such, wear and maintenance are minimal.

Fluidized-bed classifiers are commonly used for sizing applications in the silica sand and fertilizer industries. They are particularly effective for processing sand because of the stringent specifications of the aggregate industry. Complete rejection of fines and a sharp separation curve are a benefit in these applications. Fluidization water rates typically range from 10 to 30 m^3/h per square meter of separator area, depending on the feed particle size distribution and required cut point.

Processing rate is highly dependent on the feed particle size distribution, specific gravity, and required cut point. Fine feeds requiring a low cut point have the lowest capacity, whereas coarse, high-specific-gravity materials may have feed rates over 100 $t/h/m^2$. Typical feed rates for conventional fluidized-bed classifiers are shown in Figure 11 as a function of cut point for typical sand applications. In this case, the feed rates have been normalized based on the unit cross-sectional area for easy reference and comparison between machine size and shape (round vs. square).

Gravity Concentration

A fluidized-bed classifier can also be used quite effectively as a dense-media concentrator. In fact, early dense-media separators for coal washing, Chance Cones, were basically a simplified

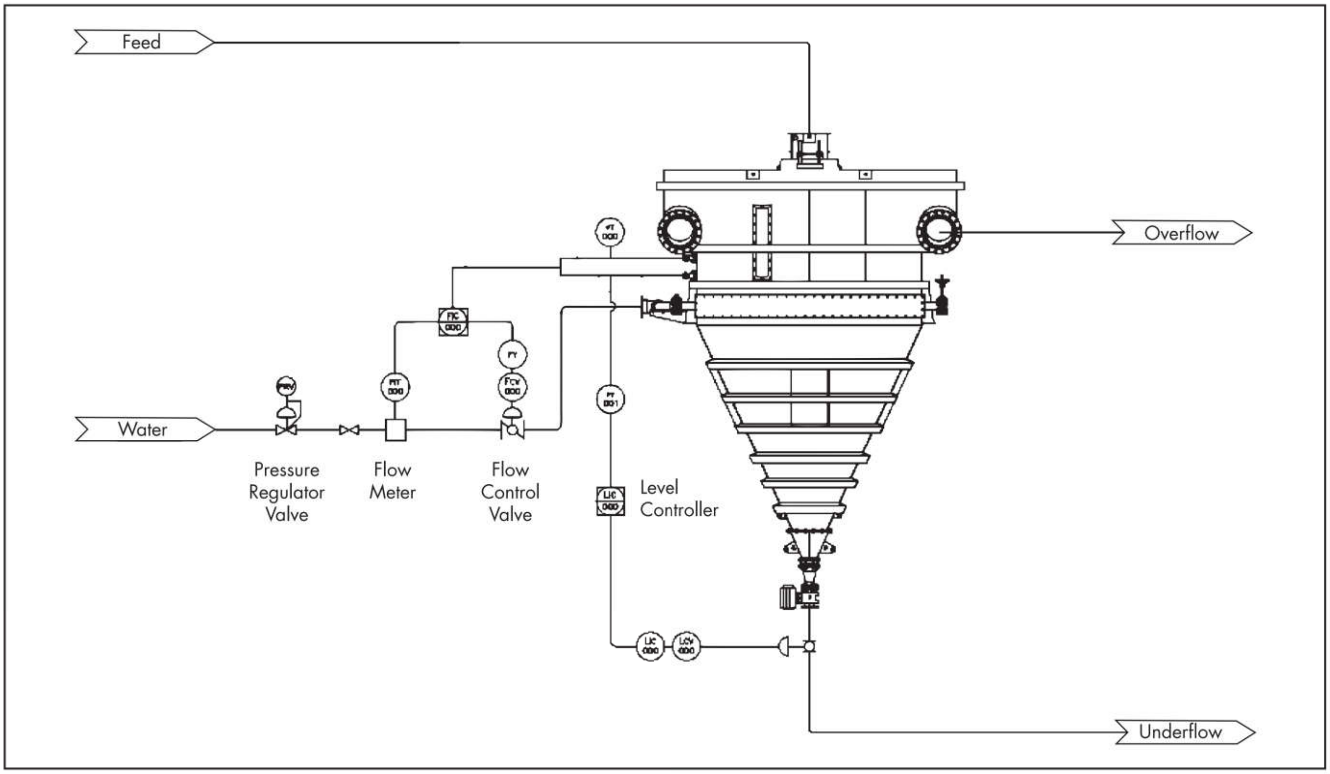


Figure 10 Modification of the standard control system utilizing differential bed pressure to adjust the fluidization rate to control the characteristics of the fluidized bed

version of a fluidized-bed classifier. In this case, a teetering bed of sand was formed in a cone using an upward flow of water, which created a fluidized bed with an effective specific gravity of about 1.6. Coarse run-of-mine coal (nominally 12–100 mm) was added to the device, and the lower-specific-gravity coal/organic fraction would float and report to the overflow along with some of the sand and water. The higher-specific-gravity rock would sink and be rejected using an underflow slide gate system. The sand was subsequently screened from each exiting stream, densified, and returned to the system to maintain the correct specific gravity for separation.

A similar situation occurs in a fluidized-bed classifier when processing a binary mineral system comprised of particles having different specific gravities. Typical applications include coal, iron ore, and heavy mineral sands. As shown in Table 1, there is a substantial difference between the specific gravity of the desired component and the gangue species in each case. In these applications, the higher-specific-gravity component will migrate toward the bottom of the unit and build a fluidized bed. The fluidized bed of high-specific-gravity material effectively creates an "autogenous" heavy media. As such, lower-specific-gravity particles are not able to penetrate the bed and will accumulate above the higher-specific-gravity particles, thereby creating an interface. The lower specific gravity materials will eventually build up and overflow the top of the separator. This approach is quite effective for gravity concentration but is restricted to a top-to-bottom particle size ratio limitation of approximately 5 or 6 to 1. Beyond this limit, the coarsest particles in the low-density material have sufficient mass to penetrate the bed and eventually report to the separator underflow stream, resulting in an efficiency reduction.

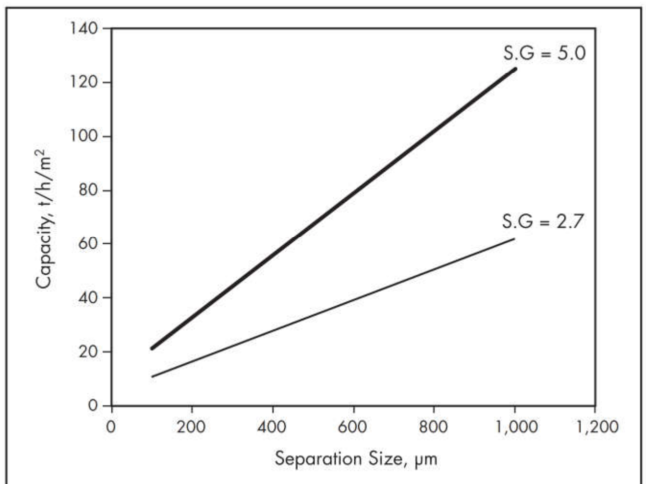


Figure 11 Typical feed mass flux rates for a conventional fluidized-bed classifier over a range of particle size cut points when treating solids with a specific gravity of 2.7 and 5.0

Table 1 Applications of gravity-based separation using fluidized-bed classifiers

Application	Specific Gravity Valuable Component	Specific Gravity Gangue
Coal	<1.6	>2.5
Iron ore	5.0–5.2	2.6
Heavy minerals sands	3.5–4.7	2.6–3.2

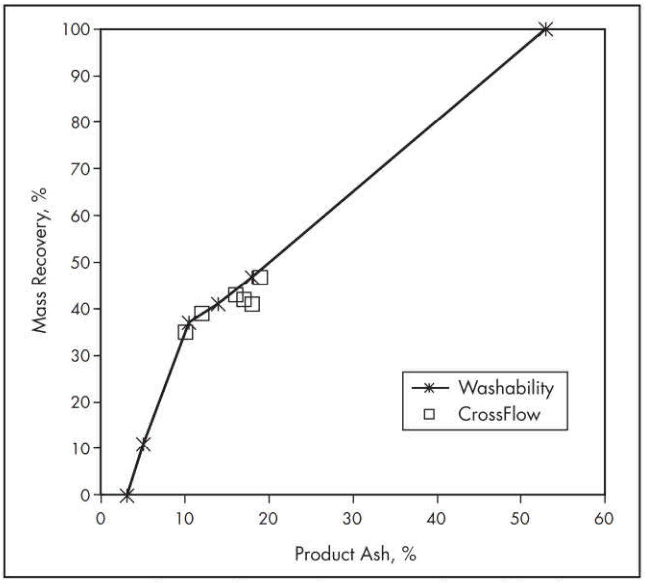


Figure 12 Coal upgrading performance achieved by the CrossFlow fluidized-bed classifier as compared to feed washability characteristics

Coal

Numerous test programs and commercial installations have been reported over the past decades for coal upgrading applications. Studies reported by others have shown that fluidized-bed classifiers can be quite effective for the recovery of fine coal when treating material in the 1.0 × 0.15-mm size range (Reed et al. 1995; Kohmuench et al. 2003, 2006). Advantages include a relatively low-density cut point, high throughput capacity per unit area, and automatic control.

Results from an eastern Australia coal using a CrossFlow separator are presented in Figure 12. The product yield (weight recovery) versus product ash content is shown in comparison to the washability data. The fluidized-bed classifier was able to produce a low-ash content product at a mass yield approaching the theoretical maximum. In this case, the organic efficiency, which is the ratio of the actual combustible recovery to the theoretical recovery at a given product ash content, approached 99%. The corresponding separation efficiency data are provided in Table 2. The overall specific gravity cut point was 1.67. Separation efficiency was relatively high as indicated by the low Ep and imperfection numbers. Separation efficiency improved with an increase in particle size while the specific gravity cut point was reduced. For the finer particle size fractions (i.e., <0.2 mm), the teeter-water flow rate overcomes the particle settling velocity thereby creating conditions that favor a particle size separation.

Iron Ore

Fluidized-bed classifiers can also be used to upgrade specular hematite. Traditionally, spiral concentrators have been used to upgrade coarse hematite after grinding to a particle size finer than ~1 mm. Although spirals work well in this application, they require a large feed distribution system and multiple stages to achieve the desired product grade and recovery. Work conducted by Venkatraman (1995) showed the advantage of using fluidized-bed classifiers in combination with spirals to simplify circuitry and improve overall metallurgical performance. In this study, a fluidized-bed classifier was used in advance of a spiral to preconcentrate the ore. The objective of the project was to produce a final iron ore concentrate containing less than 1% silicon dioxide (SiO_2) by weight while maximizing overall iron recovery. Because of the relatively large specific gravity difference between hematite and quartz, the process parameters can be set up to maximize quartz rejection with only minimal iron losses. Particle size-by-size analysis of the separated products showed that the bulk of the quartz could be rejected to the separator overflow with only minimal loss of the finest iron. The separator overflow stream containing the fine iron was subsequently reprocessed on a single stage of spirals to recover the lost values. The results from this evaluation (presented in Table 3) show that a concentrate containing less than 1% quartz can be produced with an overall circuit iron recovery greater than 96%.

Table 2 Performance results obtained using a fluidized-bed classifier to treat coal finer than 1 mm and coarser than 0.15 mm

Results	+0.60 mm	0.6 × 0.150 mm	Composite
Ep	0.073	0.105	0.081
Imperfection	0.046	0.059	0.064
SG_{50}	1.569	1.758	1.669

Table 3 Performance results for fluidized-bed classifier for 1.0 × 0.075-mm hematite

Stream Identification	Fe, %	SiO_2, %	Fe Recovery, %	SiO_2 Rejection, %
Fluidized-bed classifier underflow	68.4	0.98	59.1	92.9
Fluidized-bed classifier overflow	51.3	13.9	40.9	7.1
Spiral concentrate	68.6	0.95	89.3	95.4
Circuit product	68.5	0.97	95.7	88.6

Heavy Minerals

As noted in Table 1, because of the large specific gravity difference, heavy mineral sands are also amenable to gravity concentration using fluidized-bed classifiers. Opportunities to apply this technology to mineral sand operations were identified by McKnight et al. (1996). In this case, extensive pilot-scale test work was conducted, which led to the installation of multiple full-scale separators for zircon concentration. In this application, the separators were used to preconcentrate material feeding the zircon wet mill, which consists of numerous stages of Reichert cones and spiral concentrators. The primary objective of the wet processing plant was to reject quartz and various non-valuable aluminosilicates. The quartz/zircon separation was quite efficient because of the large density difference between the minerals. Rejection of the various aluminosilicates to achieve an acceptable zircon concentrate grade was more difficult because of the higher specific gravity of these minerals (3.2–4.0). As a result, zircon losses were often too high.

To improve process efficiency, fluidized-bed preconcentration of the zircon wet processing plant feed was evaluated. The findings are presented in Figure 13, which shows the particle size-by-size recovery for the three major components in the feed. Virtually all of the zircon was recovered to the concentrate regardless of the particle size. Only the coarsest particle size fractions (i.e., +0.25 mm) of the silica gangue were recovered, whereas the aluminosilicate recovery was around 50%. Subsequent test work confirmed that rejection of nearly all of the quartz and more than half of the near-gravity aluminosilicates provided an enhanced feedstock that greatly improved the metallurgical performance of the existing spiral circuit.

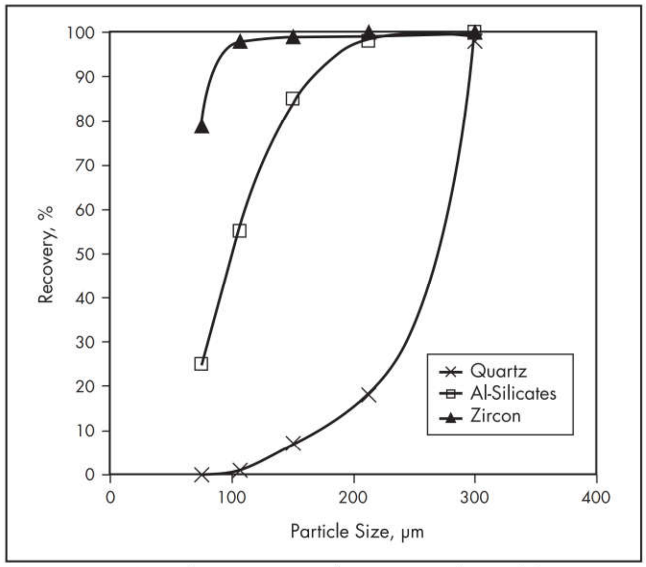


Figure 13 Mineral recovery performance achieved by a fluidized-bed classifier as a function of particle size when treating heavy mineral sands to preconcentrate zircon

MANUFACTURERS

Several different commercial units operate based on the same differential settling rate principles, including the Stokes hydrosizer (Mackie et al. 1987), Floatex (Mankosa et al. 1995; Elder et al. 2001), CrossFlow separator, Linatex hydrosizer (Deveau and Young 2005), Allflux separator, and Reflux classifier. The oldest commercial fluidized-bed classifier is the Stokes hydrosizer, which classifies particles fed into a center well located at the top of the unit. On entry, particles begin to settle against an upward flow of fluidization water that is added through a distribution plate at the bottom of the unit. The upward water velocity is set at a rate that equals the settling velocity of a certain class of particles existing in the feed. As a result, the particles in this class become suspended and create a particle bed that cumulates upward until it reaches a controlled height, which is typically a short distance from the bottom of the feed pipe. A pressure tape extends vertically through the Stokes unit to measure the pressure created by the particle bed density and height. When the bed level reaches the control height as indicated by the bed pressure, a controller opens the discharge spigot to allow coarse and/or high-density particles to pass through and report to the underflow discharge pipe. The control is set to allow continuous adjustment to the underflow rate based on the amount of coarse and/or high-density particles reporting in the underflow stream. The fine and/or low-density particles are unable to penetrate the particle bed and are carried by the fluidization water into the overflow stream of the separator.

The other commercial units have similar features but modified designs and different control systems that may enhance classification efficiency, increase capacity, and/or improve the ease of operation. The differences are detailed in the following sections.

CrossFlow Separator

One of the challenges associated with conventional fluidized-bed classifiers is that the feed is injected into the center of the unit at a depth equivalent to about one-third of the total height of the unit. This design feature causes turbulence to occur in a zone in which the large and small particles are settling toward the fluidized particle bed. In addition, the upward velocity of water is increased above the feed injection point because of the additional hydraulic loading from the water in the feed slurry. The increase in velocity results in the possibility of elutriating coarse and/or high-density particles into the overflow stream.

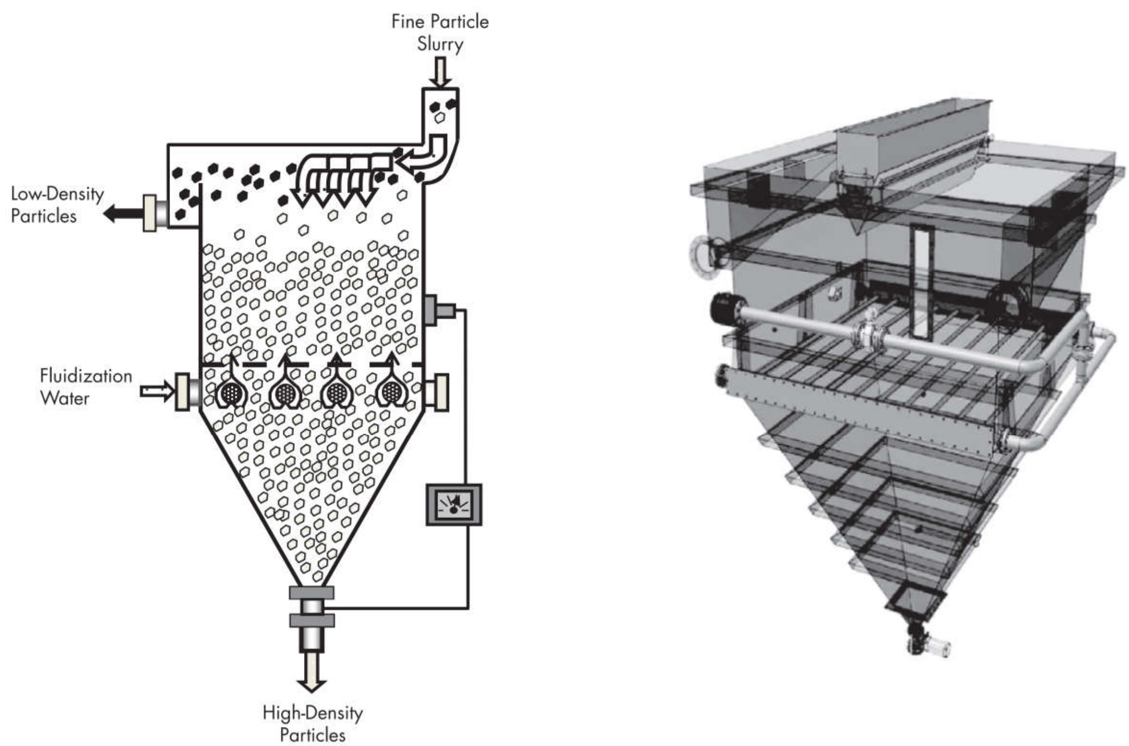
To counter this problem, Mankosa and Luttrell (1999) equipped a fluidized-bed system with a unique feed system that introduces the feed slurry across the top of the separator using a transition box, which is reflected in the commercial name for the technology, the CrossFlow separator (Figures 14A and 14B). The feed transition box increases the area of the feed introduction to the full width of the separator, which reduces velocity and turbulence. The feed flows smoothly over the top of the separator and into the overflow launder. As a result of the feed not being submerged into the teetered-bed unit, changes in feed slurry characteristics do not impact the separation performance. The upward velocity within the separator is constant throughout the vertical plane of the cell.

Linatex

The Linatex unit is a flat-bottom classifier similar to the original Stokes design. This unit also features an adjustable center well to uniformly present the feed slurry into the unit. The fluidization water enters an isolated chamber located at the bottom of the unit and is injected vertically into the fluidized particle bed through a series of nozzles. Multiple discharge values are used on large units to ensure an even drawdown of the underflow solids along the bottom of the unit. The underflow valves are cycled intermittently to minimize short-circuiting directly from the fluidized bed. Like similar units, the underflow valves are actuated based on using a control system to maintain a constant bed density.

Floatex

The Floatex Density Separator, shown in Figure 15, is similar to other devices in that it utilizes a square cross-sectional area with an internal network of teeter pipes to introduce the fluidization water. A conical bottom section is incorporated into the design to assist with dewatering the coarse underflow material prior to discharge. This feature plays an important role in controlling the rate and consistency of the underflow discharge. The high-density zone in the cone prevents material from being drawn directly from the fluidized bed, thereby eliminating the potential for short-circuiting or misplacement to the underflow. A circular feedbox with a tangential feed introduction system is used to introduce slurry into the upper portion of the separation chamber. The tangential design reduces the



A. Two-dimensional view showing the basic operating principles

B. Three-dimensional view of a commercial unit

Courtesy of Eriez Manufacturing

Figure 14 Schematics of the CrossFlow fluidized-bed classifier

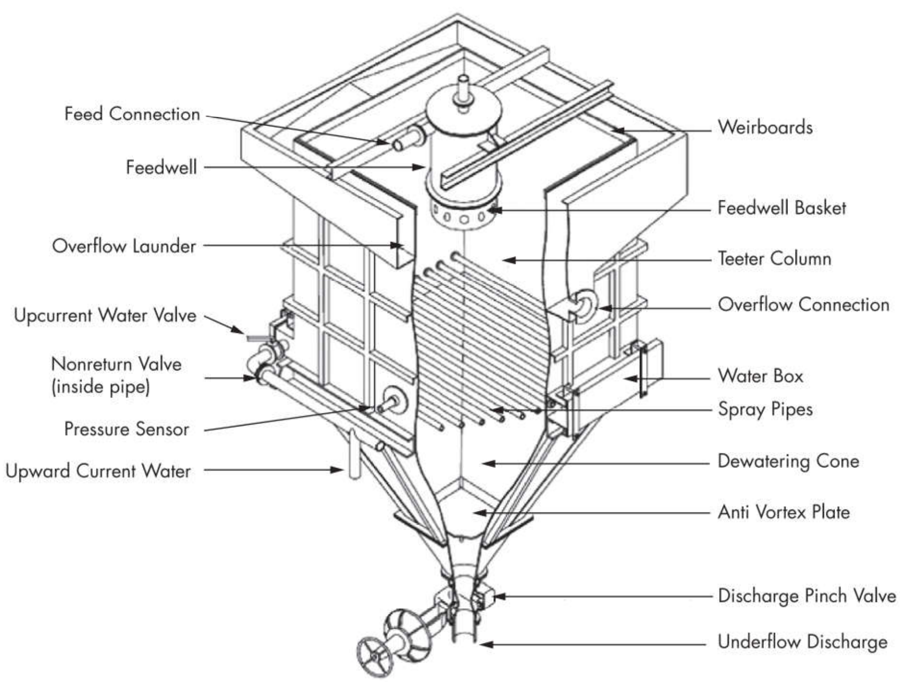
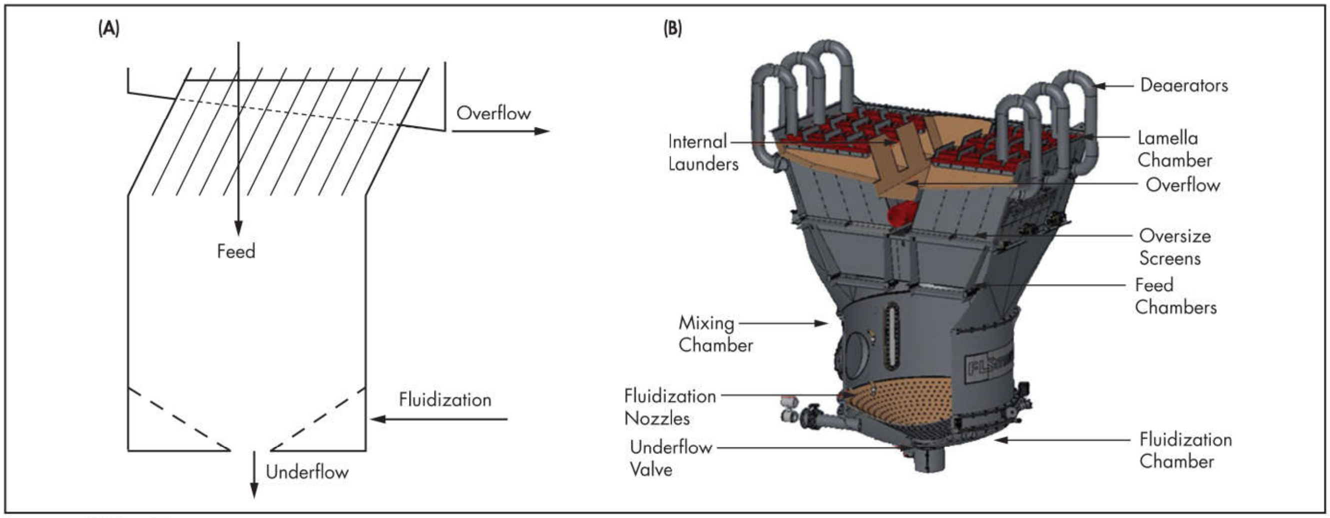


Figure 15 Floatex fluidized-bed classifier showing the feed distribution system, water manifold, teeter pipes, and underflow discharge valve



Courtesy of FLSmidth

Figure 16 Reflux classifier schematics showing (A) a basic representation with the fluidization zone and system of inclined channels and (B) a cross-sectional view of a commercial unit

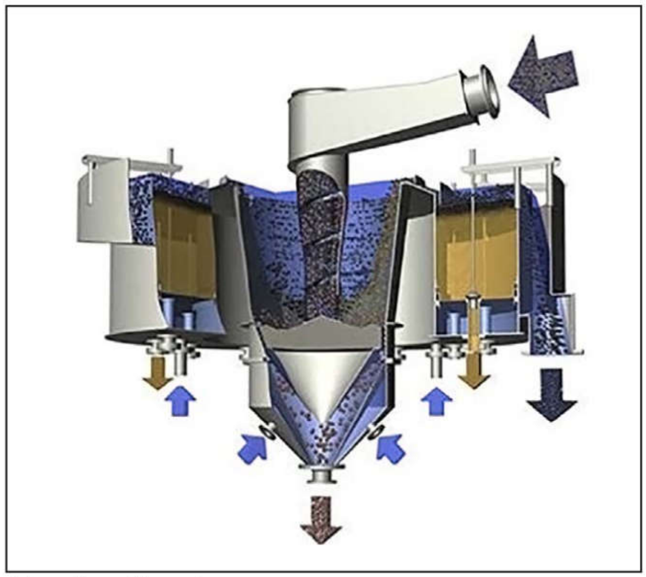
slurry velocity prior to introduction to minimize disturbances to the separation zone. Level is maintained by means of a pressure transducer and automatic underflow control valve.

Reflux

The Reflux classifier is based on the early principle of sedimentation in the presence of inclined planes originally observed by Boycott (1920). More recently, Galvin et al. (2009, 2010) discovered the particle classification benefits of using closely spaced inclined channels and developed a commercial fluidized-bed system known as the Reflux classifier. The classifier consists of a lower fluidization zone and an upper system of parallel inclined channels as shown in Figure 16A. Figure 16B shows a cross-sectional view of a commercial unit. Feed slurry enters in the middle of the machine. Relatively coarse and/or dense particles entering the lamella chamber segregate from the flow and slide downward, eventually returning to the lower fluidized-bed zone. However, fine and/or lower density particles continue to be conveyed upward through the inclined channels and into the overflow launders. This recycling or "reflux" action acts to sharpen separation characteristics, particularly for density-based concentration applications such as fine coal. The cited (Walton et al. 2010) advantage of the Reflux classifier is that the lamella-type plates decrease the unit's sensitivity to wide particle size ranges. Further, the refluxing action of the inclined channels allows the unit to efficiently treat finer particles relative to traditional hindered-bed separators.

Allflux Classifier

The Allflux classifier is a unique unit in which two stages of particle size or density-based separations are achieved in a single unit (Short et al. 2001). As shown in Figure 17, the feed is injected tangentially into the center of a cylindrical tank where the coarse, high-density particles settle to an underflow stream against a rising flow of fluidization water under the influence of a centrifugal field. The low-density particles and the fine, high-density particles overflow a partition and enter an outer separation chamber where the fine, high-density particles and/or coarse, low-density particles are fluidized by a steady stream of water injected through a screen plate and recovered in the underflow stream. The fine, low-density particles overflow into an outer weir. Since the required amount of fluidization water is subject to particle density and size, different screen decks are available to maintain an acceptable pressure drop, ensure a good distribution, and minimize turbulence.



Adapted from Allmineral

Figure 17 Cutaway view of the Allflux classifier showing feed introduction system and multiple separation compartments

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