

INDUSTRIAL APPLICATIONS OF THE CROSSFLOW SEPARATOR

J.N. Kohmuench¹
M.J. Mankosa¹
P. Venkatraman¹
G.H. Luttrell²

Laboratory and pilot-scale test data have shown that the innovative feed presentation of the CrossFlow separator provides improved metallurgy when compared to traditional hindered-bed or teeter-bed classifiers. This design feature prevents excess water from entering the separation chamber and disrupting the overall fluidization flow rate within the teeter zone. Recent side-by-side industrial-scale evaluations have verified that this technology can improve overall efficiency, reduce the cut point of separation, and increase throughput capacity. This paper describes the important features that make this novel separator ideally suited for size classification and density concentration. Test data from heavy mineral, phosphate, and industrial mineral applications are also discussed.

INTRODUCTION

HYDRAULIC SIZE CLASSIFICATION

Hydraulic separators are frequently used in the minerals processing industry to classify fine particles according to size, shape or density (Wills, 1997). Although many types of equipment exist, a device that has been gaining popularity in recent years is the teeter-bed or hindered-bed separator. The traditional design consists of an open top vessel into which elutriation water is introduced through a series of distribution pipes evenly spaced across the base of the cell. During operation, feed solids are injected into the upper section of the separator and are permitted to settle. The upward flow of elutriation water creates a fluidized “teeter-bed” of suspended particles. The small interstices within the bed create high interstitial liquid velocities that resist the penetration of the slow settling particles. As a result, small/light particles accumulate in the upper section of the separator and are eventually carried over the top of the device into a collection launder. Large/heavy particles, which settle at a rate faster than the upward current of rising water, eventually pass through the fluidized bed and are discharged out one or more restricted ports through the bottom of the separator.

Hydrodynamic studies indicate that quiescent flow/non-turbulent conditions must exist in a teeter-bed separator to maintain a high efficiency (Heiskanen, 1993). Excessive turbulence or changes in flow conditions can result in the unwanted misplacement of particles and a corresponding reduction in separation efficiency. Unfortunately, hydraulic separators typically utilize a feed injection system that discharges directly into the main separation chamber. These simplistic feed systems consist of a vertical pipe that terminates approximately one-third of the way into the main separator body. The pipe discharge is usually equipped with a distribution plate to kill the flow velocity and disperse the feed slurry, but this approach creates turbulence within the separator that is detrimental to an efficient separation. Another problem with the feed injection system is the discontinuity in flow velocity created by the additional water that enters with the feed solids and reports to the overflow launder. Below the feed point, the flow rate of water is dictated only by the fluidization water rate. This situation is desirable since it allows the operator to accurately control the separation size

- 1. Eriez Manufacturing**
Erie, PA
- 2. Virginia Tech**
Blacksburgh, VA

by adjusting the fluidization flow rate. However, above the feed injection point, the flow rate is the sum of both the feed water and fluidization water flow rates. As a result, the total upward velocity of water is higher above the feed injection point. In fact, at higher feed rates, the volume of water entering with the feed slurry may be greater than the volume flow of fluidization water. The discontinuity created by the feed water often results in a secondary interface of fluidized solids, which varies uncontrollably as the solids content of the feed varies. The increased/variable flow severely impacts the separation performance by increasing cut size, reducing efficiency (greater particle misplacement), and limiting throughput capacity.

Equipment maintenance is also an important issue in the design of a hydraulic separator. Conventional teeter-bed designs use a series of lateral pipes or a steel plate located at the base of the separation zone. These pipes and plates are perforated at regular intervals with large numbers of small diameter holes. Elutriation water is injected through these holes over the entire cross-section of the separator. The large water flow rates combined with the small injection hole diameters leave the device susceptible to blockage/plugging due to contaminants in the process water. When several orifices become blocked, a dead zone occurs in the fluidization chamber resulting in a loss of performance in this area. As a result, conventional teeterbed separators have an inherent design flaw that limits both the capacity and efficiency of the unit.

HYDRAULIC DENSITY CONCENTRATION

In addition to particle sizing applications, teeter-bed separators are also frequently used to separate various minerals based on differences in particle density. In this case, the high-density particles settle against the rising flow of water and build a bed of teetering solids segregated according to mass. This bed of solids has an apparent density much higher than the elutriation water. Since particle settling velocity is driven by the density difference between the solid and liquid phase, the settling velocity of the particles is reduced by the increase in apparent density of the teetering bed. This artificial density forces lowdensity particles to report to the overflow of the separator, and high-density particles to report to the underflow.

Some common examples of density-based teeter-bed applications include the separation of coal from rock, silica from iron ore, and silica from various heavy minerals (zircon and ilmenite). Unfortunately, plant data indicate that efficient concentration can only be achieved if the particles are in the size range of 75 microns (200 mesh) to several millimeters and if the particle size ratio (top size to bottom size) is less than about 4:1. In practice, coarse, lowdensity particles will tend to gather at the surface of the teeter-bed interface because the elutriation water velocity is not sufficient to transport these larger particles into the overflow launder. The large particles continue to gather at the teeter-bed interface until mass action forces them into the teeter bed, where they eventually are misplaced into the high-density product. This inherent inefficiency can be partially corrected by increasing the elutriation water velocity to force the coarser low-density solids into the overflow product. Unfortunately, this action has a detrimental effect on concentrate grade since it also causes the finer high-density solids to be misplaced into the overflow launder. Because

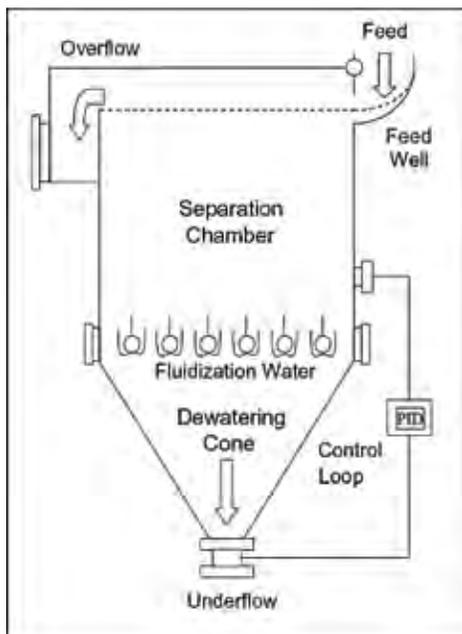


FIGURE 1
Schematic of the CrossFlow classifier

of these shortcomings, the separation efficiency obtained using teeter-bed separators is often cited as poor by industrial standards. In most cases, the valuable component frequently must be reprocessed in polishing circuits to achieve the desired product quality. The problem is that conventional teeter-bed separators, when used for density concentration, are inherently inefficient when treating particles that have either a wide size distribution or a narrow density distribution.

CROSSFLOW SEPARATOR

The CrossFlow separator has been developed as a new generation of teeter-bed separator. It incorporates several novel design features to improve process performance (separation efficiency and capacity) and reduce operating costs (power consumption and water usage). A schematic of the CrossFlow is provided in Figure 1.

Compared to a conventional hydraulic classifier, the CrossFlow design uses an improved feed delivery system that gently introduces the feed slurry across the top of the separator as opposed to injecting the slurry at a high velocity directly into the teeter-bed. As previously stated, high slurry feed volumes create turbulent mixing that has a detrimental impact on separator performance. In the new feed delivery system, the feed velocity is reduced using a transition box. The purpose of this box is two-fold. First, the feed transition box increases the flow area to the full width of the separator so that the slurry velocity, and any associated turbulence, is minimized. The second unique feature is its ability to tangentially feed the separator. This stilling-well, which is located at the top of the separator, smoothly passes the feed slurry horizontally across the top of the cell and into the overflow launder. Compared to conventional systems, the tangential feed introduction system ensures that variations in feed slurry characteristics (e.g., solids content) do not impact separator performance. In the CrossFlow, the teeter-water velocity remains constant throughout the separation chamber at all times, while the velocity in a conventional classifier generally increases above the feed addition point (Figure 2). A duck plate is also located at the discharge end of the feed well to prevent short-circuiting of solids directly to the overflow launder.

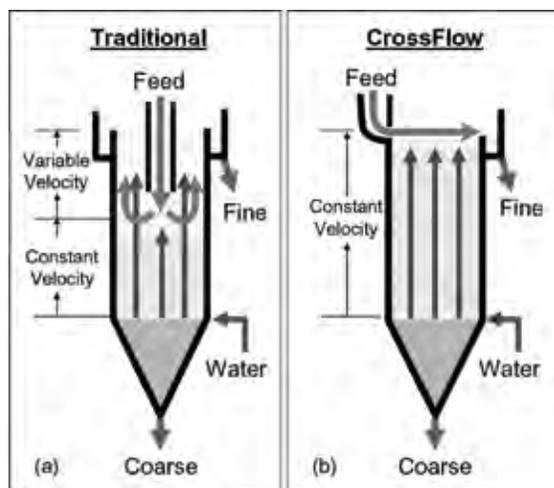


FIGURE 2
Water flow velocities in classifiers

Another design feature incorporated into the CrossFlow classifier is the improved water distribution system. A novel approach has been developed that incorporates a baffle plate to disperse the elutriation water across the base of the separator. In this design, a horizontal slotted plate is located at the base of the separation chamber. Water is introduced beneath the plate through a series of large diameter holes (>1.25 cm). However, unlike existing separators, these orifices are located at distant intervals (typically >15 cm) and serve simply to introduce the water, while water dispersion is achieved by the baffle plate. This modification essentially eliminates problems associated with plugging of distributor plates or pipes. The combined use of the improved feed injection system and simplified water distribution system makes it possible to increase both the separation efficiency and throughput capacity while eliminating mechanical problems associated with traditional designs. Because of the higher throughput capacity, the operating demands in terms of power, water consumption and maintenance are lower for the CrossFlow when reported on a per ton of concentrate basis.

Test Variable	Conventional	CrossFlow
Feed Rate (tph/m ²) Feed	20-90	10-70
Solids (%)	15-40	15-50
Water Rate (m ³ /hr)	43	9-20

TABLE 1
CrossFlow pilot-scale test conditions

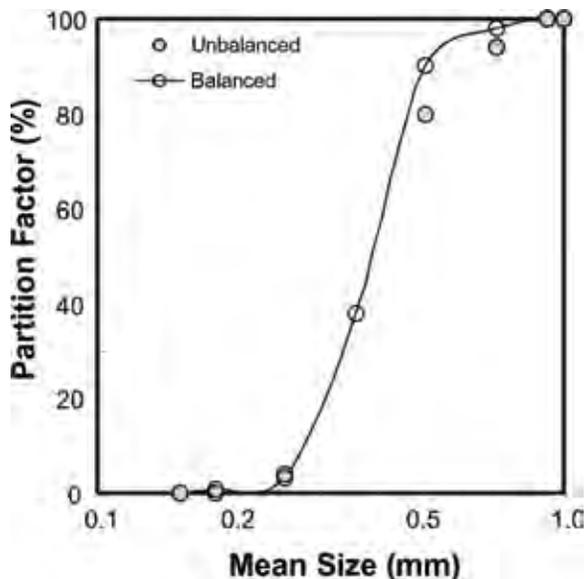


Figure 3
Example of a CrossFlow partition curve

CLASSIFICATION

PILOT-SCALE TESTS

An on-site test program was conducted at an industrial phosphate plant to evaluate the potential benefits of the CrossFlow separator for particle classification. The 0.6x0.6-m (2x2-ft) pilot-scale unit was installed to partition the 1.0x0.1-mm (16x150 mesh) plant feed for the existing flotation circuits into narrowly-sized fractions. Comparison tests were also performed using a pilot-scale conventional classifier so that any improvements in sizing performance could be accurately quantified. Table 1 provides a summary of the operating conditions examined for each classifier. For each test, representative samples were collected from the feed, overflow, and underflow. The samples were subjected to sieve analysis and the results were mass balanced using a sum-of-least-squares method to assess the reliability of the experimental data. Data that mass balanced poorly were deemed unreliable and eliminated from the analysis.

The mass balanced data were used to construct partition curves for each test run performed for the two classifiers. Figure 3 shows an example of a partition curve obtained using the CrossFlow separator. The partition number represents the recovery of dry solids from the feed to the underflow (oversize) product for each size class. The partition curves were used to determine the imperfection (I) for each test. The imperfection is a dimensionless number commonly used to quantify the efficiency of sizing units. A lower number represents a steeper curve and thus a better separation. A vertical line represents a perfect separation. The imperfection (I) is determined by:

$$I = (d_{75} - d_{25}) / 2d_{50} \quad [1]$$

Using this approach, the test results were analyzed to compare the performance of each separator. These results, which are compared in Figure 4, show the imperfection of each unit as a function of dry feed rate. The test results indicate the CrossFlow unit consistently performed at a higher level of efficiency (i.e., lower imperfection). Close examination of the test results indicated that the lower efficiency associated with the conventional classifier was due to misplacement of coarse material to the overflow product created by the higher flow rate and greater turbulence within the upper section of the conventional sizer. On the other hand, the CrossFlow hindered-bed separator maintained a uniform (laminar) flow pattern and thus the amount of misplaced material was minimized.

It is also important to note that the unique design of the CrossFlow makes it possible to accurately control the particle cut size. The cut size is defined as the particle size corresponding to the 50% recovery point on the partition curve, and is considered to be separation size for a given test. As stated previously, variations in the characteristics of the feed (such as solids content) do not significantly impact the cut size since the teeter water velocity remains constant throughout the unit. As a result, the particle cut size is controlled predominantly by the teeter water flow rate. In fact, the data in Figure 5 show that an approximately linear relationship exists between flow rate and particle cut size. As a result, on-line adjustment of size of the overflow and underflow products can be achieved through simple water flow control for the CrossFlow classifier.

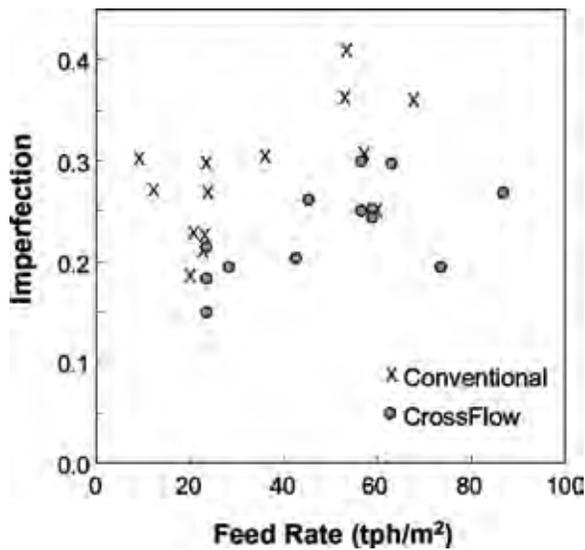


Figure 4
Imperfection vs. solids feed rate

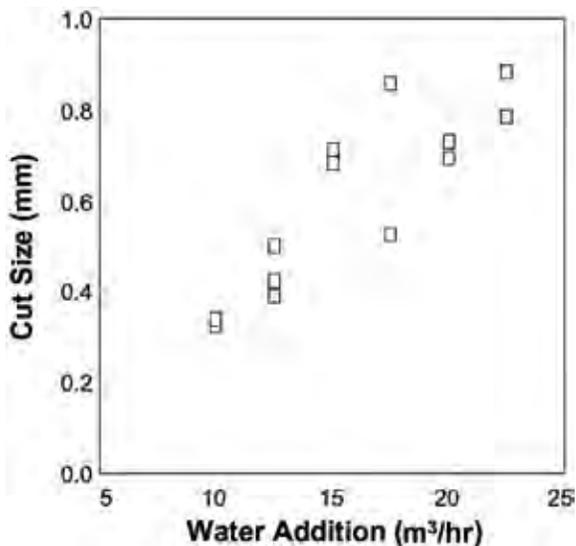


Figure 5
Cut size vs. fluidization water rate

FULL-SCALE TESTS

In light of the promising results obtained using the pilotscale CrossFlow unit, a full-scale classifier at an industrial phosphate beneficiation plant was retrofit using the CrossFlow feed introduction system. The data obtained from the retrofitted unit were then compared to those obtained from the conventional full-scale classifiers operating in parallel. Due to fluctuations in the plant feed tonnage, the test results are reported as an average of seven sets of experiments conducted over a range of circuit feed rates from 1400 to 1980 tph (1270 to 1800 stph). In each test, representative samples of feed, oversize and undersize solids were collected and subjected to sieve analysis. The resulting size data were used to construct partition curves for both the conventional and CrossFlow units. The data points were then fit using an empirical partition function given by:

$$P = (\exp\{\alpha(d/d_{50})\} - 1) / (\exp\{\alpha(d/d_{50}) - \exp\{\alpha\} - 2) \quad [2]$$

in which P is the partition factor, d is the particle size, d_{50} is the particle size cut point (defined at P=50%), and α is a parameter that reflects the sharpness of the size separation (defined as the slope at P=50%). Note that a larger value of α indicates a sharper (more efficient) particle size separation.

The results of the side-by-side comparison of the conventional and CrossFlow classifiers are provided in Table 2. The test data show that the CrossFlow reduced the particle cut size from 729 to 362 microns while maintaining the same feed throughput. At the same time, the CrossFlow substantially improved the efficiency of sizing (alpha was increased from 3.4 to 8.1). In fact, the amount of misplaced coarse (+0.425-mm) solids in the fine product overflow was reduced by more than five-fold (from 9.0% to 1.7%). These impressive results illustrate the superior performance of the CrossFlow separator for industrial classification applications.

A second round of testing was completed in order to compare the two classifiers at a similar particle size cut point. Since the particle cut size had been reduced simply by changing the feed arrangement, the teeter water and effective density of the retrofitted unit were adjusted until the cut size between the two units were similar. Presented in Table 3 are the results of this comparison. In addition, Figure 6 shows the separation curves for the two units normalized to their respective cut points. It is easily seen that the retrofitted classifier offers a much sharper separation curve when compared to the existing unit. A comparison of the Imperfections indicates that the retrofitted separator operated with a 33% higher efficiency.

Test Variable	Conventional	CrossFlow
Particle Cut Size	729 μ m	362 μ m
Alpha Value	3.4	8.1
Misplaced +0.425 mm	9.0%	1.7%

Table 2
Comparison of full-scale classifiers

Test Variable	Conventional	CrossFlow
Particle Cut Size	490 μm	420 μm
Alpha Value	3.2	7.2
Imperfection	0.162	0.109

Table 3
Comparison of full-scale classifiers

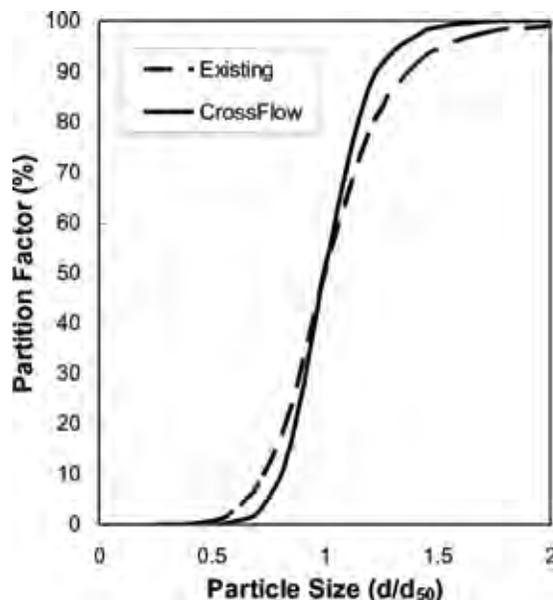


Figure 6
Separation curves for industrial sizers

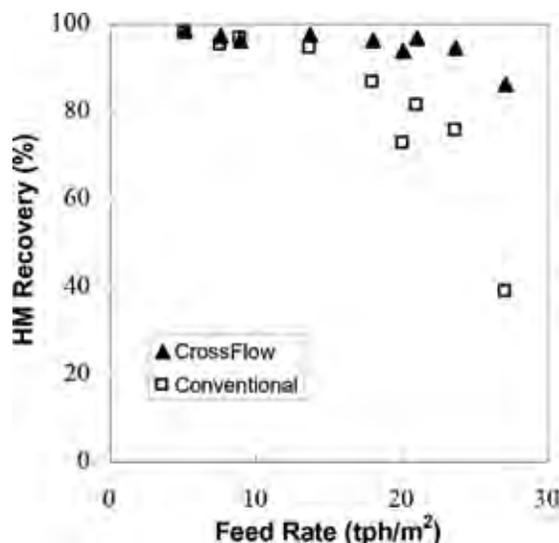


Figure 7
Capacity tests (after Dunn et al., 2000)

DENSITY SEPARATION

PILOT-SCALE TESTS

The use of hindered-bed separators for heavy mineral beneficiation has long been examined. Dunn et al., 2000, reported that the Allflux® separator has been tested successfully in concentration applications including quartz sands, iron ore, and heavy minerals. Also, several coal cleaning applications have been successfully tested (Reed et al., 1995, Kohmuench et al., 2005). Successful use of the Floatex Density Separator to recover zircon from previously rejected mill tailings was also demonstrated (McKnight et al., 1996).

Further investigation by Dunn et al., 2000, indicated that hindered-bed separators offer heavy mineral recovery in excess of 95% while rejecting approximately 90% of the quartz contaminants from a wet mill concentrate. In these studies, the product grade averaged 33% TiO_2 and 95% heavy mineral. Furthermore, it was reported that the CrossFlow feed presentation system offered a significant capacity advantage over other teeter-bed technologies.

Figure 7 shows the results from capacity tests undertaken in this work. Specifically, the CrossFlow was shown to have a clear capacity advantage. At a target heavy mineral recovery of 95%, the CrossFlow was shown to have a capacity 1.8 times that of a conventional unit. It was concluded that this increase in capacity was a result of the elimination of the high velocity zone in the upper section of the teeter-bed. In addition, as a direct result of the higher capacity, the overall teeter water requirement for the CrossFlow system was 60% of the conventional system.

FULL-SCALE UNITS

Follow-up testing conducted by Eisenmann (2001) evaluated the performance of the CrossFlow separator at a wider range of operating parameters. The overall performance curves for all tests are presented in Figure 8. As shown in this Figure, heavy mineral recovery ranged between 90% and 100% with quartz rejection up to 75%. The benefits of rejecting the quartz contaminants from the wet mill concentrate include reduced transportation, scrubbing, and drying costs. It is also anticipated that the subsequent dry mill and zircon upgrade processes will be improved (i.e., more efficient) due to the higher grade of the feed for each of the downstream unit operations. Based on these findings, a full-scale CrossFlow has been purchased and is currently being installed.

Other evaluations included work on a South American barite sample. Laboratory test work indicated that the CrossFlow separator was able to achieve a BaSO_4 (SG 4.5) recovery greater than 90% while simultaneously rejecting, on average, over 90% of the SiO_2 (SG 2.65) contaminant. In fact, due to the success of the initial test work, a second round of testing was implemented to confirm the metallurgy. The final underflow product was assayed at better than 98% BaSO_4 with a silica content of less than 1%.

Based on these results a full-scale separator was installed and commissioned in 2002. Figure 9 shows the average plant metallurgy with respect to the two sets of pilot-scale test runs. This figure indicates that a good correlation was achieved between the pilot and full-

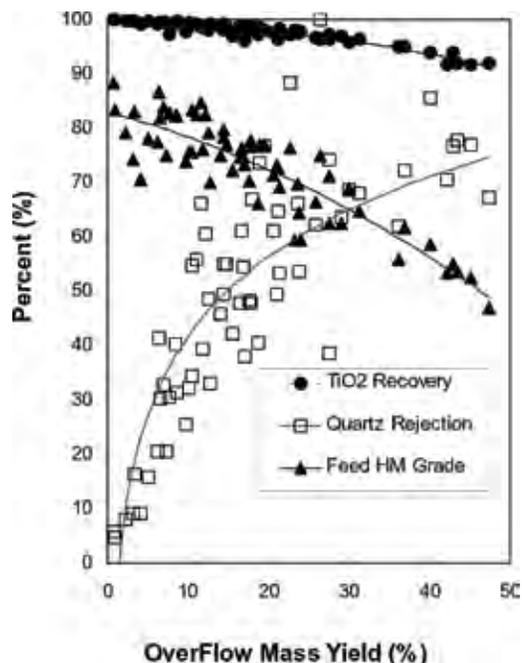


Figure 8

CrossFlow testing of heavy mineral concentrate (after Eisenmann, 2001)

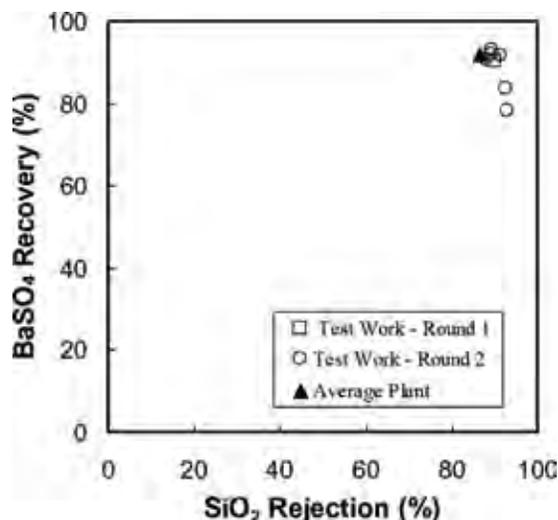


Figure 9

Pilot and full-scale results for barite

Unit Size	100x400 mm	50x200 mm
Feed Rate	23 tph/m ²	23 tph/m ²
Feed Solids	60%	65%
Teeter-Water Rate	10.2 tph/m ²	20.0 tph/m ²
Acid Feed Rate	12% (w/w)	7% (w/w)
product pH	6.1	6.4-6.7

Table 4

Acid Washing Test Work for Heavy Material

scale units. As shown, the plant averaged approximately 90% Barite recovery at a silica rejection of 90%. In general, scale-up for teeter-bed separators is straightforward provided that the flow per square area of separator area is maintained relatively constant. This ensures that the velocity and hindered-settling profiles under both the pilot and full-scale approaches are consistent.

ACID WASHING

PILOT-SCALE TESTS

Acid leaching is used in heavy minerals beneficiation for the treatment of zircon. Specifically, acid is used to improve the surface properties of the mineral by removing iron coatings. Typically, a high concentration of sulfuric acid is mixed with the zircon ore at high temperature. However, the elevated acidity of the ore must then be neutralized to a range between 5 and 8 for materials handling and customer requirements.

Unfortunately, equipment such as belt filters and hydrocyclones can retain up to 45% of the acidic liquor due to the moisture content of the cake or the water split within the cyclone. This results in a poor rejection of the acid (i.e., 90%). Even after several stages of conventional washing, a large amount of residual acid may remain with the zircon. In fact, to get a reasonable removal of acid, up to eight stages of washing may be required. The logarithmic nature in which pH is measured can exacerbate this problem, as even a 99% rejection of acid can result in only a modest increase in pH.

As such, the CrossFlow separator was evaluated for increasing the pH of the zircon product. The continuous upward current of teeter water offers an infinite number of washes when compared to either hydrocyclones or belt filters. The counter-current nature of the device helps to improve the washing action as the freshest teeter-water initially contacts the particles with the highest pH and continually makes its way upward through the separator, contacting increasingly acidic particles. Secondary benefits include i) the comparatively small amount of acidic liquor generated and ii) a relatively small footprint when compared to other processes such as multi-stage belt filter and hydrocyclone circuits.

In this evaluation the unit was operated with nearly 100% of the solids reporting to the underflow. The teeterwater rate was adjusted until the bed was adequately suspended. Feed rates ranged between 10 and 25 tph/m². Offered in Table 4 are the laboratory results from this test work.

FULL-SCALE UNITS

Based on the performance achieved in the laboratory evaluation, two full-scale units were installed and commissioned to neutralize a low pH zircon feed. Two 1.2x1.2-meter (4.0x4.0-ft) cells were chosen for this application. A single taller unit was originally nominated for this duty; however, a dual stage circuit was preferred due to height restrictions and to ensure failsafe performance. Data from site indicate that the final zircon product pH ranges between 7 and 8, which is better than anticipated. This is most likely the result of the elevated pH of the plant water supply.

SUMMARY

Laboratory, pilot, and full-scale evaluations have shown that the innovative feed presentation system utilized in the CrossFlow separator has several benefits which are a direct result of preventing excess water from entering the separation chamber and disrupting the fluidization rate within the teeter-zone. These benefits include an overall improvement in separation efficiency, a reduction in the separation cut size, and an increase in throughput capacity. Specifically,

1. Pilot-scale testing has shown that the CrossFlow feed presentation system offers improved separation efficiency in comparison to conventional hindered-bed classifiers.
2. A subsequent full-scale retrofit of an existing hydrosizer with a CrossFlow feed system verified that at equivalent cut points, the classification efficiency is improved by more than 33%.
3. Teeter-bed separators provide an efficient separation between valuable heavy mineral and silica gangue in a wet mill concentrate. In addition, data indicate that the CrossFlow feed presentation system offers a higher unit capacity and lower water requirement when compared to conventional units.
4. A full-scale CrossFlow separator was installed for a barite application that showed good correlation between laboratory data and the full-scale units. Typical results show that over 90% of the available barite can be recovered at a silica rejection of greater than 90%.
5. Hindered-bed separators offer an efficient means of reducing the pH of heavy mineral ore. The teeter-bed action within the separator gives each particle an infinite amount of washes in a single stage. Full-scale data show that typical zircon ore can be effectively neutralized using this technology (pH 1.5 vs. pH 7-8).

ACKNOWLEDGEMENTS

The authors would like to acknowledge and thank the multiple industrial representatives that participated in this test campaign. Their contributions in terms of time, manpower, expertise, and direct financial support are gratefully acknowledged. In addition, the authors acknowledge the financial support provided by the U.S. Department of Energy (DE-FC26-03NT41789) Industries of the Future Program which funded portions of this test work.

REFERENCES

1. Dunn, P.L., Stewart, S.O., Kohmuench, J.N., and Cadena, C.A., 2000. "A Hydraulic Classifier Evaluation: Upgrading Heavy Mineral Concentrates," *Preprint 00-155*, SME Annual Meeting, February 28 - March 1, 2000, Salt Lake City, Utah.
2. Eisenmann, M.D., 2001, *Elutriation Technology in Heavy Mineral Separations*, Master's Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, 160 pp.
3. Heiskanen, K., 1993. *Particle Classification*, Chapman & Hall, London, England, 321 pp.
4. Kohmuench, J.N., Davy, M.S., Barnett, G.D., and Barnett, P.J., 2004. "Hindered-Bed Separations for Coal Cleaning Applications," *Tenth Australian Coal Preparation Conference, Proceedings*, Polkolbin, New South Wales, Australia, October 17-21, 2004, pp. 116-128.
5. McKnight, K., Stouffer, N., Domenico, J., and Mankosa, M.J., 1996, "Recovery of zircon and other economic minerals from wet gravity tailings using the floatex density separator," *SME Annual Meeting*, Phoenix, Arizona, March 11-14.
6. Reed, S., Roger, R., Honaker, R.Q., and Mankosa, M.J., 1995, "In-plant testing of the Floatex density separator for fine coal cleaning," *Proceedings, 12th International Coal Preparation Conference*, Lexington, Kentucky, pp. 163-174.
7. Wills, B.A., *Mineral Processing Technology*, 6th Edition, Butterworth-Heinemann, Boston, Massachusetts, 486 pp.



Eriez Flotation Division | Canada Inc
7168 Venture St
Delta, BC, V4G 1H6
Canada
Office: +1 604-952-2300
efdca@eriez.com