

# DESIGN, OPERATION, AND CONTROL OF A TEETER-BED HYDROSEPARATOR FOR CLASSIFICATION

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## ABSTRACT

Teeter-bed (i.e., hindered-bed) separators are used throughout the mineral processing industry for both classification and density separation. The high capacity and sizing characteristics of these units make them ideal for feed preparation prior to coarse flotation (+0.100 mm) circuits. Teeter-bed separators are typically easy to control with two basic operating parameters including fluidization water rate and bed level. However, data show that these two parameters greatly interact with one another. Given this finding, a high-level automatic control scheme was developed and implemented on a full-scale separator. In addition, dialogue with plant operators has led to several simple changes to an already established design that improves operational and maintenance characteristics.

## INTRODUCTION

Hydraulic separators are frequently used in minerals processing for sizing applications. Of these devices, the teeter-bed or hindered-bed separator (TBS) continues to be a mainstay within the mining industry. Typically, these devices are open-top vessels through which elutriation water is injected. This water is commonly distributed across the base of the cell through a series of distribution pipes or perforated plating.

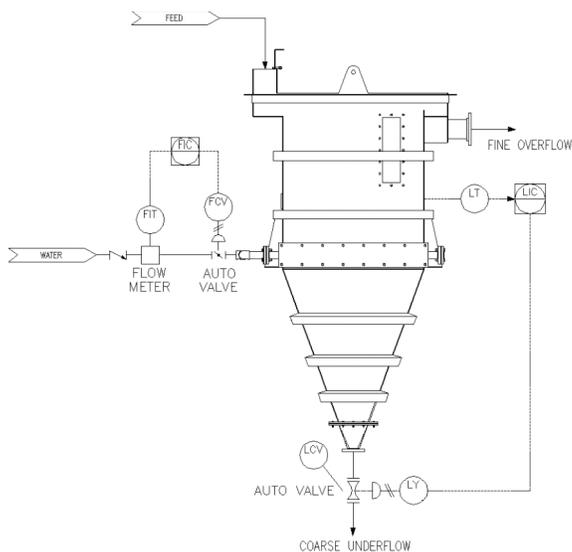
During operation, feed solids are introduced into the upper section of the separator and are permitted to settle. The upward flow of elutriation water creates a fluidized “teeter bed” of suspended particles. The small interstices within the bed create high interstitial liquid velocities that resist the 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.

The separation provided by a teeter-bed separator is governed by the following:

$$U_i = \frac{gd^2(\phi_{max} - \phi)^\beta (\rho_s - \rho_f)}{18\eta(1 + 0.15Re^{0.687})} \quad [1]$$

where  $U_i$  is the hindered-settling velocity of a particle,  $g$  is the acceleration due to gravity,  $d$  is the particle size,  $\rho_s$  is the density of the solid particles,  $\rho_f$  is the density of the fluidizing medium,  $\eta$  is the apparent viscosity of the fluid,  $\phi$  is the volumetric concentration of solids,  $\phi_{max}$  is the maximum concentration of solids obtainable for a given material, and  $\beta$  is a function of Reynolds number ( $Re$ ).

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**FIGURE 1**  
Typical control system for TBS units.

It should be noted that Equation [1] was derived from an expression advocated by Masliyah (1979) and modified utilizing relationships offered by Richardson and Zaki (1954) and Swanson (1989). An in-depth derivation of Equation [1] is not reviewed here but offered elsewhere (Kohmuench et al. 2002 and 2006).

By inspection of Equation [1], it can be determined that both the size of a particle and its density greatly influence how that particle will settle within a hindered state. As such, teeter-bed separators are frequently used in the minerals processing industry to segregate fine particles according to size, shape or density (Wills, 1997). Typically, if a size distribution is very tight and there is a large variation in particle specific gravity (e.g., mineral sands), then a teeter-bed separator can be used to segregate material based on density. Likewise, if a size distribution is very wide and the density distribution is relatively tight (e.g., silica sands), a teeter-bed separator can be successfully utilized as a classifier.

## CONTROL

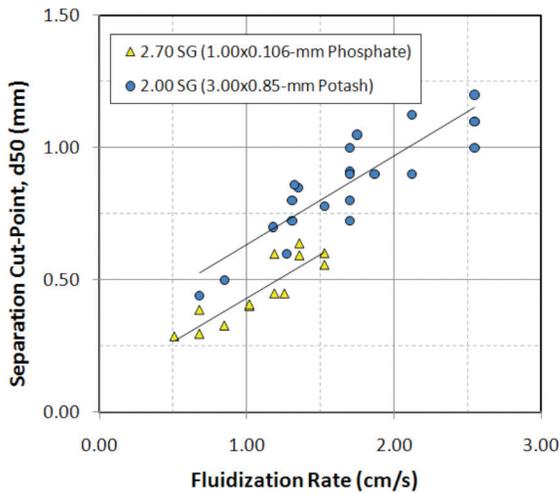
Teeter-bed separators are considered operator-friendly and simple to control. Traditionally, there are only two primary control variables which include i) the fluidization rate and ii) the teeter-bed level. The fluidization rate is the amount of water that is injected across the cross-section of the cell against which the material must settle. The teeter-bed level is essentially an indication of the weight of the material held up within the device.

This basic control scheme is illustrated in Figure 1. In this approach, feed is presented to the separator and allowed to settle against the upward current of the fluidization medium which in most cases is process water. The water rate can be controlled manually or automatically using a simple PID control loop. In this latter approach, a flow meter (FIT) provides feedback information to a flow indicating controller (FIC) that makes adjustments to an automatic flow control valve (FCV) in order to maintain the fluidization flow constant.

The bed level is controlled in a similar manner where the weight of material within the separator is measured using a pressure sensing device. The pressure sensing device is typically a pressure or level transducer (LT) that can be mounted to the side of the unit or suspended from above. It should be noted that this indication of level is commonly, but incorrectly, referred to as a density reading. Regardless, the pressure sensor provides a feedback signal to a level indicating controller (LIC) that makes adjustments to an automatic underflow control valve (LCV) to maintain a constant bed level.

## FLUIDIZATION (TEETER-WATER) RATE

Given that the particles must settle against the upward current of fluidization flow within a teeter-bed separator, it is clear that this operating parameter has the most direct influence on separation cut size ( $d_{50}$ ). As a result, the teeter-water rate is considered a coarse tuning parameter and must be sufficient to maintain the bed fluid. If the teeter-water rate is insufficient, the material within the separator will sand-out and no separation will occur.



**FIGURE 2**  
Cut-point vs. fluidization rate

Data show that there is generally a linear relationship between fluidization rate and the separation cut-point ( $d_{50}$ ). The relationships for two different mineral applications are shown in Figure 2. Included in this figure are data for classification of 1.00x0.0.106-mm phosphate matrix. As seen, a fluidization rate between 0.5 and 1.5 cm/s provides a range of cut points between 0.25 and 0.65 mm. Also shown in Figure 1 are data for a 3.00x0.85-mm potash application. In this case, cut points range from 0.4 to 1.2 mm for fluidization rates of 0.6 to 2.5 cm/s.

As expected, the denser phosphate requires a higher fluidization velocity to affect the same cut-point as the less dense potash (2.7 vs. 2.0 SG). However, there is only a moderate difference in the medium rise velocity for a given cut-point. This result can be attributed to the influence of other process variables including the feed particle size distribution and the liquid medium characteristics. In this example, the potash is significantly coarser than the phosphate. In addition, it should be noted that the potash classification is carried out using saturated brine as the liquid medium ( $\rho_f = 1.24$  SG) which influences the hindered-settling velocity as seen in Equation [1]. The higher liquid specific gravity effectively raises the apparent density within the separator and increases the cut point when compared to process water ( $\rho_f = 1.00$  SG).

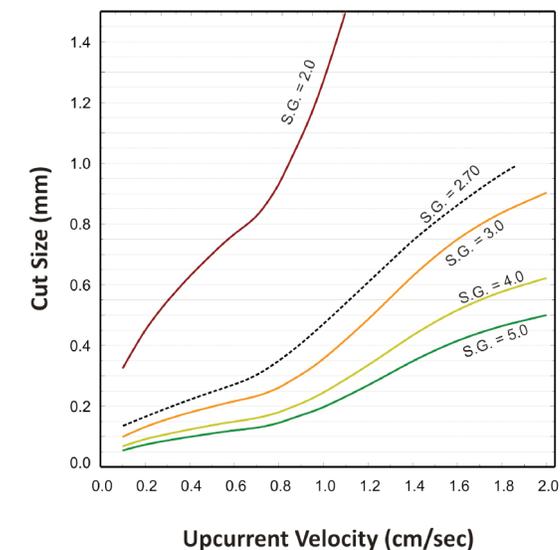
The effect of mineral density is more clearly seen in Figure 3. In this figure, cut size ( $d_{50}$ ) is shown as a function of upward current velocity for various mineral densities. As seen, denser material requires a greater rise velocity in order to achieve the same separation cut point. In other words, it takes a greater amount of flow to adequately fluidize denser particles and maintain them in a hindered suspension.

### TEETER-BED LEVEL (BED PRESSURE)

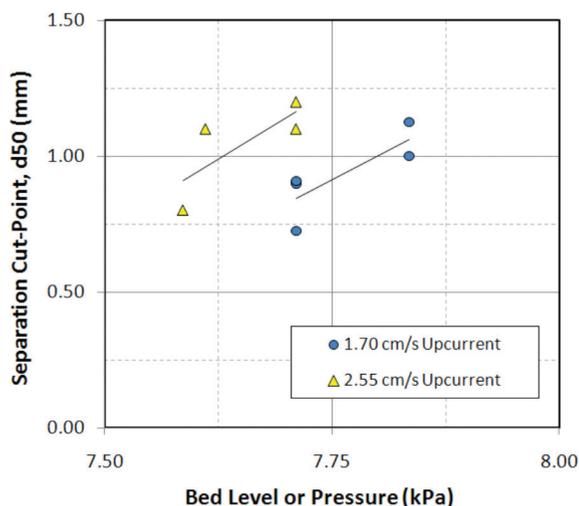
Unlike the fluidization rate which expands or contracts the teeter bed, the bed-level adjustment is used to modify how much material is retained inside the separator. As such, bed level can be considered a fine tuning parameter which modifies the height or accumulation of particles within the teeter bed. As more coarse material is held up within the separation chamber, the apparent weight of the suspension is increased.

A typical response of separation cut-point versus bed pressure is provided in Figure 4. Two cases are provided that show the effect of bed pressure on the separation cut-point for both a relatively low (1.70 cm/s) and high (2.55 cm/s) fluidization rate. It can be seen in each case that as the bed pressure increases, the separation cut point also increases.

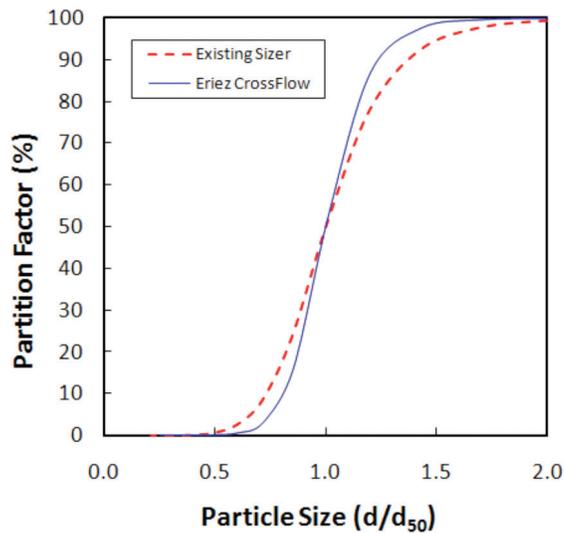
This trend is not surprising given that a teeter bed in a classification operation consists of particles that are being segregated based on size and hindered-settling velocities. As such, the finest material with the slowest settling velocity will accumulate near the top of the teeter bed and the coarser particles with the highest settling rate will penetrate the teeter bed and accumulate at the bottom of the separation chamber. Changes in the bed pressure set point effectively dictate the overflow weir level with respect to particle size.



**FIGURE 3**  
Cut-Point vs. teeter rate using water as a fluidizing medium for various particle densities.



**FIGURE 4**  
Effect of bed level on cut point ( $d_{50}$ )



**FIGURE 5**  
Separation curves for industrial sizers

## CLASSIFICATION EFFICIENCY

There are several means of measuring the overall efficiency of a classification unit operation. The typical approach includes using material-balanced data to construct a partition curve for the separation. An example of two partition curves is provided in Figure 5. The partition factor represents the recovery of dry solids from the feed to the underflow (oversize) product for each size class.

The partition curve is used to determine the separation accuracy by approximating the slope of the line at the cut point ( $d_{50}$ ). This value is typically reported as the Ecart Probable ( $E_p$ ) error, i.e.:

$$E_p = \frac{d_{75} - d_{25}}{2} \quad [2]$$

where  $d_{75}$ ,  $d_{50}$ , and  $d_{25}$  represent the size at which 75%, 50%, and 25% of the feed mass reports to the underflow of the separator, respectively. It should be noted that a lower  $E_p$  value reflects a steeper curve and thus a better separation. A vertical line represents a perfect separation.

$E_p$  values vary with  $d_{50}$ . As such, a more useful term is Imperfection ( $I$ ) which allows for the direct comparison of separations that occur at different cut points. As seen in Equation [3], Imperfection is simply the  $E_p$  normalized to the  $d_{50}$ :

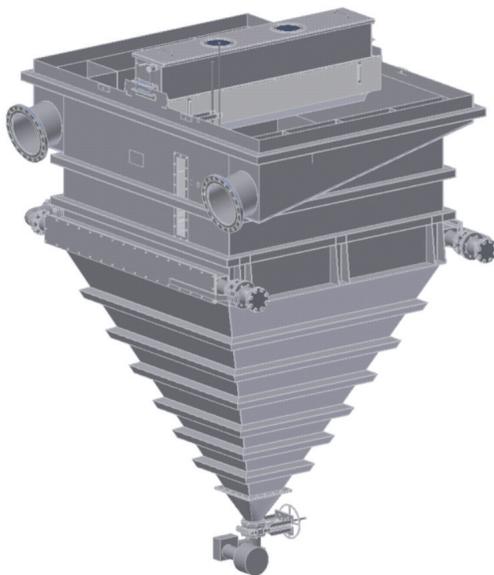
$$I = \frac{E_p}{d_{50}} \quad [3]$$

As shown by Luttrell et al. (2006), an alternative approach to determining the relative sharpness of the separation is to fit measured sizing data by using an empirical partition function such as:

$$P = (\exp\{\alpha(d/d_{50})\} - 1) / (\exp\{\alpha(d/d_{50})\} - \exp\{\alpha\} - 2) \quad [4]$$

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  $\alpha$  is a parameter that reflects the sharpness of the size separation (defined as the slope at  $P=50\%$ ). Note that unlike  $E_p$  or Imperfection, a larger value of  $\alpha$  indicates a sharper (more efficient) particle size separation.

The data in Figure 5 illustrate a case study in which two side-by-side units were compared with respect to sizing efficiency. In this case, one of two existing hydraulic classifiers was retrofitted with an Eriez CrossFlow feed presentation system. The CrossFlow design (See Figure 6) 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. Feed is effectively presented horizontally across the top of the cell towards the overflow launder. Compared to conventional systems, the tangential feed introduction 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 and also minimizes turbulent mixing which can be detrimental with regard to performance.



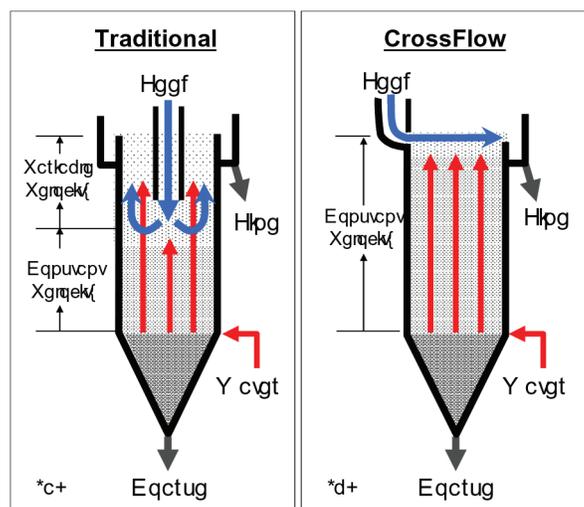
**FIGURE 6**  
3D model of CrossFlow Separator

Test Variable	Existing	CrossFlow
Test 1 - Particle Cut Size Alpha Value Misplaced +0.425-mm	729 $\mu\text{m}$ 3.4 9.0%	362 $\mu\text{m}$ 8.1 1.7%
Test 2 - Particle Cut Size Alpha Value Imperfection	490 $\mu\text{m}$ 3.2 0.162	420 $\mu\text{m}$ 7.2 0.109

**TABLE 1**  
Comparison of full-scale classifiers

The results of the side-by-side comparison of the existing and CrossFlow classifiers are provided in Table 1. The test data show that for the initial test during which only the feed presentation system was changed (i.e., all other operating variables equal), 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%).

A second round of testing was completed in order to compare the two classifiers at a similar particle size cut point. Since the separation cut point had been reduced simply by changing the feed arrangement, the teeter water and bed level of the retrofitted unit were adjusted until the cut size between the two units was similar. The separation curves for the two units normalized to their respective cut points are shown in Figure 5. It is easily seen that the retrofitted classifier offers a much sharper separation curve when compared to the existing unit. A comparison of the separation curves indicates that the retrofitted separator operated with a 33% higher efficiency.



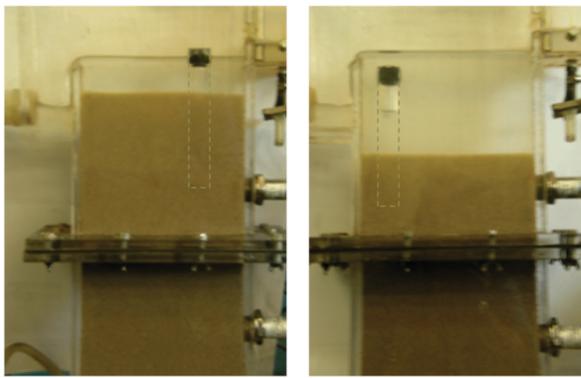
**FIGURE 7**  
Water flow velocities in classifiers

## IMPROVING OPERATION & CONTROL

The design of the CrossFlow Separator is based on maintaining a constant, quiescent and precise upward velocity within the separation chamber of the unit. 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, conventional hydraulic separators typically utilize a feed injection system that discharges directly into the main separation chamber which creates excessive turbulence. A larger issue 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. The conventional approach greatly increases the rising water velocity at or above the feed entry point. As a result, the volume of water entering with the feed slurry at higher feed rates is likely greater than the volume flow of teeter water required for proper particle fluidization. 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 (See Figure 7).

Some classifiers utilize a flat-bottom arrangement. In this approach, one or more underflow discharge nozzles are placed directly beneath or in close proximity to the fluidization system. In this case, there is no clear delineation between the fluidization zone and the underflow discharge area. As a result, the underflow stream will be relatively dilute given that the material is being pulled from an area of low percent solids. More importantly, the underflow solids content will vary significantly as the underflow valve opens and closes which can greatly vary the upward fluidization velocity.



(a) 5 Lpm – Low Bed Density  
(b) 3 Lpm – High Bed Density

**FIGURE 8**  
Effect of water velocity on bed density

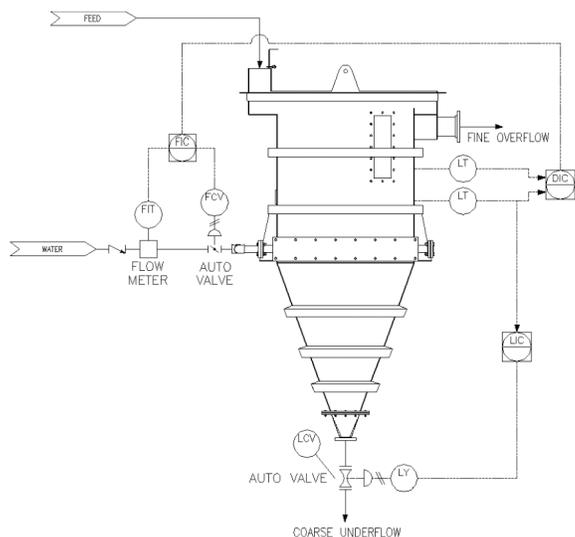
A dewatering cone is used to improve overall control and to manage these fluctuations by maintaining a constant water-split within the separator. In essence, this cone is located underneath the separation chamber. As particles settle past the teeter pipes, they drop into this sanded zone and move via mass-action to the underflow valve. The purpose of the dewatering cone is to force the maximum amount of liquid out of the coarse stream, thereby creating a highly dewatered product. Under normal operating conditions, the solids content of this underflow stream will remain very consistent (+/- 2%). As a result, the upward water flow rate also remains very consistent, which improves separation efficiency.

The importance of proper fluidization control and how this parameter can greatly affect bed density and particle settling rates is seen in Figure 8. In this illustration, a known amount of silica sand is fluidized in a laboratory-scale (50 x 200-mm) CrossFlow Separator. Two cases were investigated which included the use of both high and low fluidization rates. In Figure 8a, the sand is fluidized using 5 Lpm of process water. As seen by the relative position of the sand-water interface, the bed is expanded to within 50 mm of the overflow weir. In the second example (Figure 8b), the sand is fluidized with only 3 Lpm of process water. As a result, the sand-water interface has dropped significantly. It should be noted that no sand has been added or removed from the system during this exercise.

More importantly, a free-floating, small glass vial partially filled with sand, water, and air was positioned in the teeter zone to act as a visual reference for density. In the 5 Lpm case, the bed is highly fluidized and expanded. While the top of the teeter bed is high, the relative density of the teeter bed is quite low with the glass jar nearly submerged. In contrast, at the lower fluidization rate, the bed contracts and the voids between the suspended particles become smaller. As a result, the relative density is quite high with the glass jar less than half submerged. The higher density within the teeter zone provided additional buoyancy to the vial.

The complex interaction between fluidization flow, bed level, and the calculated bed density is also revealed through inspection of Figure 5 which was previously presented. In this figure, bed level readings are shown for the same application while using two fluidization rates. It is seen that the higher fluidization rate resulted in lower bed level readings (at the same cut point) which is a clear indication of bed expansion. From above, it can also be deduced that a greater degree of expansion will result in lower calculated bed densities. While the interaction between these parameters can be challenging to quantify, each are measurable and therefore, susceptible to automatic control.

Based on these observations, a new process control strategy was implemented by Eriez for managing the various operating parameters of teeter-bed style separators. In this approach (See Figure 9), two transducers are utilized instead of a traditional single pressure sensor. These sensors are installed at different elevations but in close proximity to one another. The lower sensor is used to control the bed level as previously described. This sensor provides the process input for a level indicating control (LIC) which proportionally opens and closes the underflow valve (LCV) to maintain the mass above the sensor constant.



**FIGURE 9**  
Updated control system for TBS units

The upper pressure transducer is used in conjunction with the bottom sensor in order to calculate the true density of the teeter zone located between the sensors. This bed density ( $\rho_b$ ) is calculated using the following equation derived from first principles:

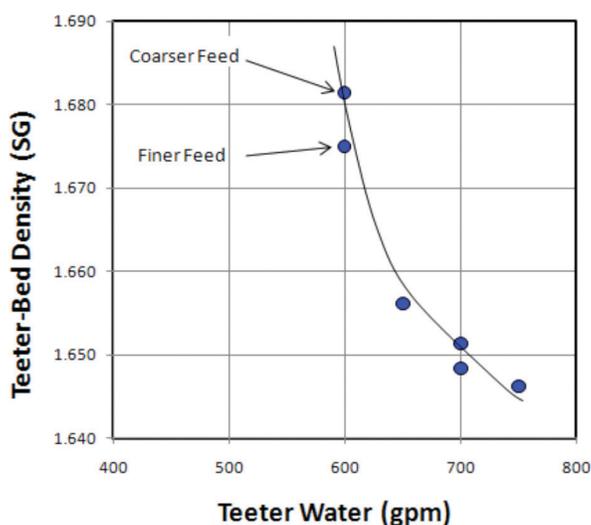
$$\rho_b = \frac{\Delta P \times A}{V_z} = \frac{\Delta P}{H} \quad [5]$$

where  $\Delta P$  is the differential pressure reading calculated from the two pressure transducers,  $A$  is the cross-sectional area of the separator,  $V_z$  is the volume of the zone between the two sensors, and  $H$  is the elevation difference between the sensors. This calculated parameter is monitored by a density indicating controller (DIC) which then finely adjusts the fluidization flow in order to maintain the bed density stable. This control scheme can be advantageous in situations where feed or product characteristics change on a regular basis (e.g., particle size distribution or solids content).

### FULL-SCALE CASE STUDY - CONTROL

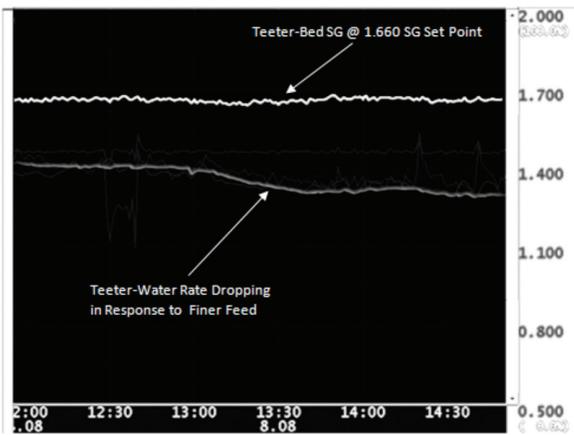
A teeter-bed based separator was installed at a Florida phosphate beneficiation plant. The original control scheme for this separator included the use of manual control valves for the adjustment of the fluidization water rate. Unfortunately, the feed characteristics were constantly changing due to variable operator settings and natural matrix inconsistencies. For example, when the feed to the separator became significantly coarser, the teeter bed would be insufficiently fluidized (i.e., sanded). As a result, operators hedged against this occurrence by operating at relatively high fluidization rates which resulted in misplacement of material during normal operation or when the feed size distribution became much finer.

To combat these issues, the existing separator was outfitted with an automatic process water flow control valve and a separate differential pressure transducer. This allowed the separator to be controlled as shown in Figure 9. Prior to automating the teeter-water addition rate, the response of calculated bed density with varying teeter-water rate was investigated. A clear correlation between these two parameters was established as seen in Figure 10. In addition, it was found that with all other operating parameters equal, coarser feed will affect an increase in bed density due to its greater mass and required fluidization rate. In contrast, fine feed will result in a lower bed density and fluidization rate.



**FIGURE 10**  
Teeter water and density correlation

Given the clear correlation seen in Figure 10, the circuit was placed in automatic control. For the purpose of proving the concept, a teeter-bed density of 1.660 SG was chosen as the operating set point. As such, the density indicating control supplied a continuously updated set point for the teeter-water control in order to maintain a constant bed density. This approach provided for an extremely stable process as demonstrated by flat line trending produced by the plant distributed control system (DCS) as seen in Figure 11. This figure illustrates the controlled response during a period when the feed particle size distribution became significantly finer. As such, the teeter-water rate was reduced in order to maintain the calculated bed density of 1.660 SG.



**FIGURE 11**  
Example of bed-density control

## FLUIDIZATION SYSTEM MAINTENANCE

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 teeter-bed separators have an inherent design flaw that limits both the capacity and efficiency of the unit.

In contrast, the CrossFlow separator incorporates another design feature that improves water distribution. A novel approach has been developed that incorporates a slotted 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) which are significantly larger than the largest particle. 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.

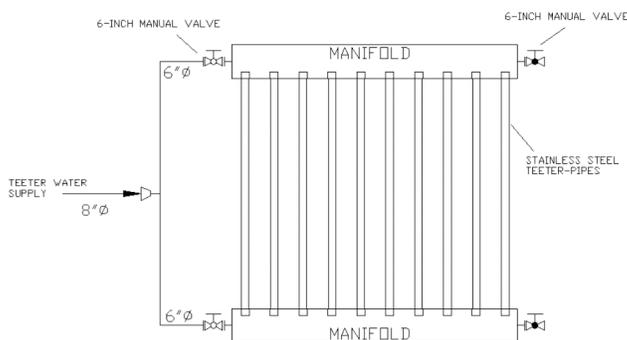
In addition, the water distribution system incorporates a check valve to prohibit backflow and manifold valves that facilitate clean-out in the unlikely event of a plugging issue. This arrangement includes manually actuated valves which are located on the end of each manifold as seen in Figure 12. This approach allows each manifold to be easily flushed by diverting flows from one side of the unit to the other.

## SUMMARY

Teeter-bed separators are efficient classification devices that provide a means to separate coarse and fine material according to hindered-settling relationships. Material characteristics and operating variables such as fluidization water flow and bed level can greatly affect the separation. As such, it is important to understand how these parameters interact with one another.

### IN GENERAL:

1. The fluidization rate is considered a coarse tuning parameter. Data show that there is a linear relationship between teeter-water addition rate and the separation cut-point ( $d_{50}$ ).
2. Bed level is considered a fine tuning parameter allowing for subtle changes in separation cut point ( $d_{50}$ ). An increase in bed level increases the  $d_{50}$  by allowing more material to accumulate within the teeter zone of the separator.



**FIGURE 12**  
Typical manifold and valve arrangement

3. The classification efficiency of teeter-bed separators is commonly quantified through examination of partition curves. The Ecart Probability ( $E_p$ ), Imperfection ( $I$ ), and Alpha ( $\alpha$ ) are common terms used to define the steepness (i.e., sharpness) of the slope of these separation curves at the process cut point.
4. Through the examination of partition curves generated from a full-scale investigation, an Eriez CrossFlow Separator was shown to provide an improved separation when compared to a traditional classifier. This improvement is attributed to the more efficient management of the water that arrives with the feed solids.
5. An improved control strategy was implemented based on laboratory and field observations. This control method involves adjusting teeter-water rates to maintain a constant calculated bed density. A second pressure transducer is required for this approach which provides additional control stability for variable processes.
6. This improved control strategy was implemented on an industrial scale at a Florida phosphate plant. By monitoring and correcting for the calculated bed density, operating parameters were automatically adjusted to combat the changes in feed characteristics.
7. Given that ease of maintenance is an important aspect for reliable service, additional improvements were made to the teeter pipe and manifold arrangement to facilitate clean-out of the fluidization system in the unlikely event of fouling.

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