Separation magnetism

Daniel Norrgran and Jaisen N. Kohmuench, Eriez, US, examine new developments in coal preparation equipment

Figure 1. Suspended electromagnet. The magnet is suspended over the conveyor belt to remove ferrous tramp from the coal prior to crushing.

Increasing energy demands and the generation of new power plant capacity worldwide have escalated the demand for coal. New levels of coal production have been reached in recent years. Accordingly, there have been new developments in process equipment focused on increasing the recovery of coal as well as providing and maintaining a high level of productivity.

Eriez has made several advances in equipment specific for coal preparation plants. The following are some of the major developments in coal processing equipment.

- Suspended electromagnets to remove tramp iron and protect downstream equipment from damage and unscheduled maintenance.
- Wet drum magnetic separators for the continuous recovery of magnetite in the heavy media circuit.
- Hydraulic separators for the upgrading of fine coal in the -2 mm (-10 mesh) range.
- Column flotation cells for the recovery of fine coal -0.150 mm (-100 mesh).

Suspended magnetic separators for tramp metal removal

The practice of using magnetic separators to collect ferrous metal from process streams has had a long history in the mining industry. The first application and the most prevalent application today is the removal of ferrous tramp from conveyor belts. This is a straightforward application suspending an electromagnet over the conveyor belt. A typical example is illustrated in Figure 1. The magnet removes tramp metal that represents a potential hazard to downstream crushers, mills, pulverisers and grinders. The magnet can also be mounted over feeders or chutes.

There have been significant developments in the design and manufacture of suspended electromagnets. The 1220 mm to 1520 mm (48 to 60 in.) wide coal conveyor belts once considered large have evolved to between 1830 mm and 2440 mm (72 to 96 in.) wide. Suspended magnets have increased in size and magnetic field strength accordingly.

Suspended magnets - components

The electromagnet consists of an electromagnetic coil with a cylindrical steel core positioned in a steel housing. The coil magnetically induces the steel core, which in turn projects a magnetic field for the collection of tramp metal. The coil and core are submerged in transformer oil to dissipate heat. The components are shown in Figure 2.

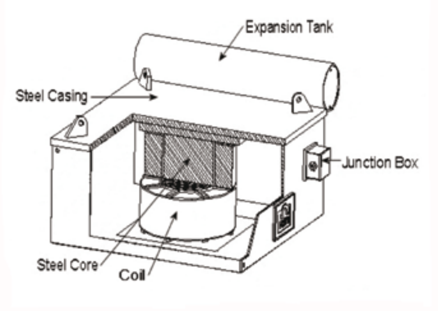

Figure 2. Major components of a suspended electromagnet.

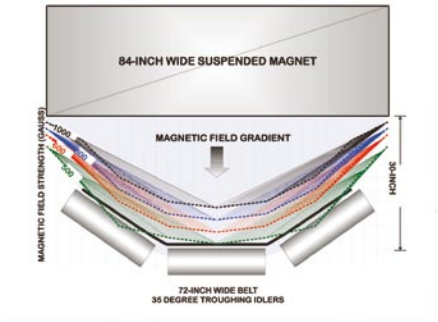

Figure 3. Typical magnetic field configuration of a suspended electromagnet.

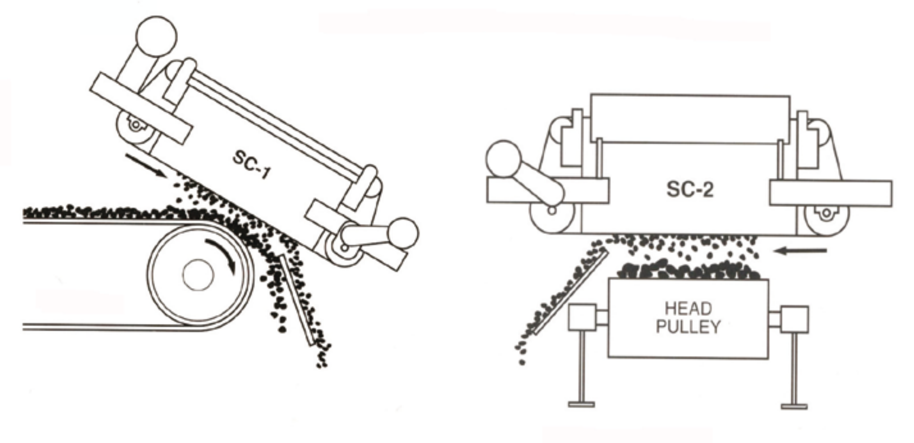

Figure 4. Positioning of suspended electromagnets. In-line position is over the trajectory discharging the head pulley. Cross-belt is over the conveyor belt prior to the head pulley. Manual clean or self-cleaning magnets may be utilised. Pictured are self-cleaning magnets. These magnets utilise a cross belt to discharge collected ferrous tramp.

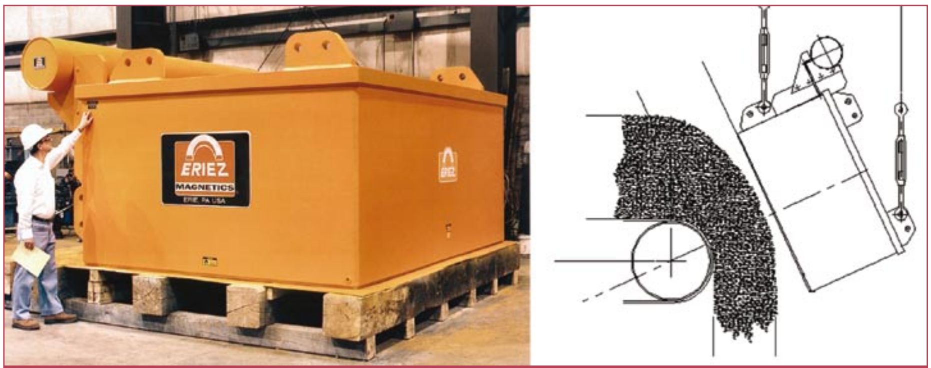

Figure 5. Manual cleaning electromagnet 3810 mm (150 in.) wide designed for a 3050 mm (120 in.) wide conveyor belt. The magnet was installed over the head pulley at a 40 in. suspension height. This magnet weighs 59 t and operates at 35 kW.

A power supply is used to energise the magnet. The power supply converts the alternating current input to direct current output to energise the coils.

Suspended magnets - magnetic circuit design

The coil design and the subsequent power draw are the two first order variables in the design of the electromagnet and the projected magnetic field. The coil must be sufficiently large in combination with minimised power to allow for convection cooling. Furthermore, this design extends the life of the conductor insulation and subsequently the life of the electromagnet.

Magnetic circuit modelling and optimisation of the electromagnet is now carried out using multi-dimensional finite element analysis. This methodology provides an accurate depiction of the magnetic field configuration. The modelling provides analytical assessment of the power input, the magnetic field strength and the thermodynamic properties.

Suspended magnets - magnetic field strength

The suspended electromagnet is typically configured with a cylindrical steel core that is induced to project a magnetic field downwards onto the surface of the conveyor belt. The magnetic field extends from the core out to the edges of the magnet box. This magnetic field configuration approximates the cross-section profile of a conveyor belt running on idlers as shown in Figure 3.

Suspended electromagnet selection

The foremost factor in electromagnet selection is the burden depth of the material on the conveyor belt. Note that the belt speed, belt width, capacity, and bulk density all are factors in the material burden depth on the conveyor belt. The burden depth and subsequent idler height determines the suspension height of the magnet and consequently the effective magnetic field strength required at the conveyor belt surface.

The suspension height is the distance between the face of the magnet and the conveyor belt.

Suspended electromagnets are mounted in one of two positions over a conveyor belt as shown in Figure 4. In position 1, the magnet is mounted just over the stream of material leaving the head pulley. This position utilises the full potential of the magnet as it reacts with the material in suspended trajectory. Tramp metal is easily pulled through the suspended burden. Furthermore, the flow of material is directed towards the magnet face. Collection of the tramp metal from the material flow does not necessitate a change in direction. At conveyor belt speeds of less than 350 ft/min., the suspended trajectory of the material is minimal and becomes near vertical. In this case the magnet must be shifted to a position approaching directly over the head pulley.

In position 2, the magnet is mounted over the conveyor belt prior to the head pulley. This position requires higher magnetic field strengths to attract the ferrous component, shift the direction of momentum, and pull it through the bed of material.

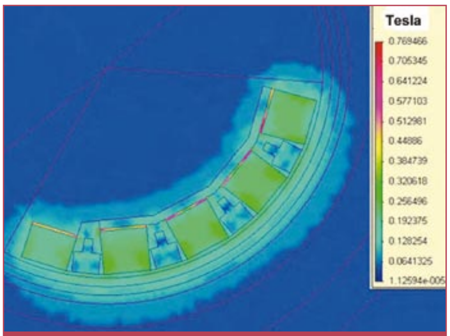

Figure 7. Finite element analysis and modelling of a wet drum magnetic element. Contour plot details magnetic field intensity and magnetic field gradient.

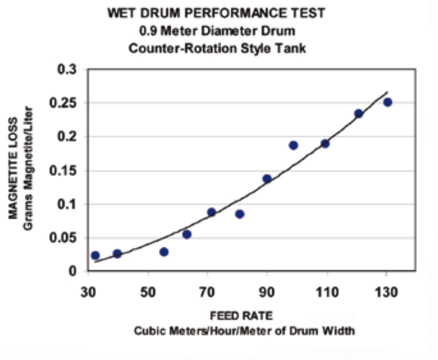

Figure 8. Wet drum magnetic separator performance. Magnetite loss as a function of feed rate.

Figure 6. Wet drum magnetic separators for heavy media application. Self-levelling counter-rotation tank style.

Suspended electromagnets are available as a manual cleaning style or a self-cleaning style. Manual cleaning magnets are best suited where only small amounts or occasional pieces of tramp metal are encountered. The magnet must be periodically turned off in order to remove tramp iron accumulation from the magnet face. Self-cleaning magnets employ a cross-belt running around the magnet face to provide continuous removal of collected tramp iron.

Experience dictates that the operating magnetic field strength or the magnetic field strength at the belt surface should generally be in the 500 to 600 gauss range for adequate ferrous collection. As the magnet width increases to accommodate the belt width, the magnetic field strength also increases. This is simply the case that a wider magnet has a larger core and coil. By design, the larger coil has more amp-turns and operates at a higher magnetic field strength.

Suspended magnets - high capacity conveyor belts

Very large electromagnets have been developed to accommodate increasing conveyor belt widths and capacities. Suspended magnets ranging up to 3810 mm (150 in.) wide and appropriate for conveyor belt widths up to 3050 mm (120 in.) are in operation. A large electromagnet is shown in Figure 5. Electromagnets for high capacity conveyor belts require a thorough assessment of the specific application. These electromagnets are designed and engineered for continuous operation taking into account the required magnetic field configuration as well as the thermodynamic properties.

Wet drum magnetic separators

Over the years, the perception of wet drum magnetic separators has transformed. Innovations in both magnetic circuit design and materials of construction have been applied to wet drum magnetic separators to maximise magnetite recovery and minimise wear and maintenance. A wet drum magnetic separator that was once viewed as a necessary ongoing expense may now be viewed as an avenue to significant cost savings to the operation. Wet drum magnetic separators commonly used in heavy media coal circuits are illustrated in Figure 6.

Wet drum magnetic separators - feed factors affecting drum performance

In a wet drum separator, the magnetic force acting on a ferromagnetic particle is predominately opposed by hydrodynamic drag force. This feature, when properly applied, provides the vehicle of separation washing away the non-magnetic particles while the ferromagnetic particles are collected in the magnetic field. The hydrodynamic drag force is also responsible for any losses of ferromagnetism. The sizing of the wet drum magnetic separator is primarily based on the slurry volume and the magnetic loading.

Wet drum magnetic separators - components

Magnetic circuit modelling and optimisation of permanent magnetic circuits is now carried out using multi-dimensional finite element analysis. The input is a scale design of the magnetic circuit; the output is a contour plot of the generated magnetic field intensity and the magnetic field gradient. This methodology provides an accurate depiction of the magnetic field configuration as shown in Figure 7. The North American industry standard is the Eriez 950 gauss Interpole magnetic element.

The counter-rotation wet drum tank style is preferred for heavy media applications. The drum rotates against the slurry flow in the counter-rotation tank style. Any magnetite that is not immediately collected will pass through to a magnetic scavenging zone. The short path that the magnetic material must be conveyed between the feed entry point and the magnetics discharge lip, combined with the magnetic scavenging zone, results in high magnetite recoveries.

Essentially all wet drum tanks used in heavy media applications have levelling spigots and a full width overflow that must be maintained during operation. A deviation in the overflow may result in inefficiencies in the performance and the loss of magnetite. A modification of the counter-rotation wet drum tank represents a recent development in technology for heavy media wet drum magnetic separators. The self-levelling tank has no discharge spigots to adjust or monitor and maintains a constant slurry level at any flow rate.

Wet drum magnetic separators - sizing and separator parameters

The purpose of the wet drum magnetic separator is to recover magnetite in the heavy media circuit. When properly applied, the magnetic loss to the wet drum non-magnetic effluent will be reduced to less than 0.25 g of magnetite/l of effluent. This generally equates to a magnetite recovery in the 99.8 to 99.9% range. In order to meet this performance, a number of conditions must be satisfied, including magnetic field strength, tank design, and various feed slurry parameters.

Slurry volume is one primary factor in sizing wet drums. Magnetite recovery is directly related to the unit capacity or flow rate through the separator. As the flow rate increases, the slurry velocity and consequently the fluid drag force increases, which tends to detach or wash away magnetite particles from the opposing magnetic field.
Hydraulic capacity is measured as m^3/hr of slurry/m of drum width.

Magnetic loading or the amount of magnetite in the feed slurry is the other primary factor in sizing wet drum magnetic separators. Any given wet drum magnetic separator has the characteristic of removing a limited amount of magnetite based on the diameter of the drum, peripheral speed, and the magnetic field strength. Magnetic loading is measured as tph of magnetite/m of drum width.

In heavy media applications, the magnetic loading is based on a value which will give the minimum acceptable loss to the non-magnetic product. Much higher loadings are possible, but will result in progressively exceeding the magnetic tailings concentration goal of 0.25 g of magnetite/l of effluent. At high levels of magnetics in the feed slurry, a reduction in the feed rate or unit capacity of the separator will be necessary to achieve acceptable magnetite recoveries.

The slurry sizing parameters as well as the magnetic loading parameters for the 0.9 m and 1.2 m diameter wet drum magnetic separators are provided in Table 1.

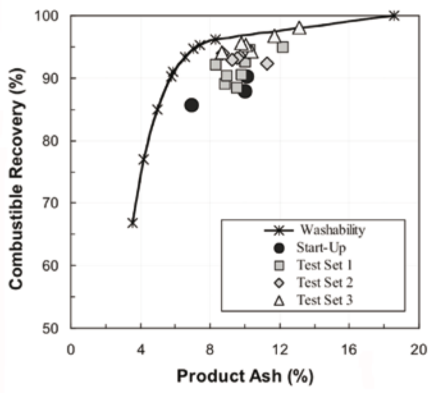

Figure 11. Results of CrossFlow full-scale evaluations versus washability data.

Figure 12. 4.6 m (15 ft) diameter CoalPro column flotation cell with an adjustable wash water system. The wash water removes entrained clays from the coal froth.

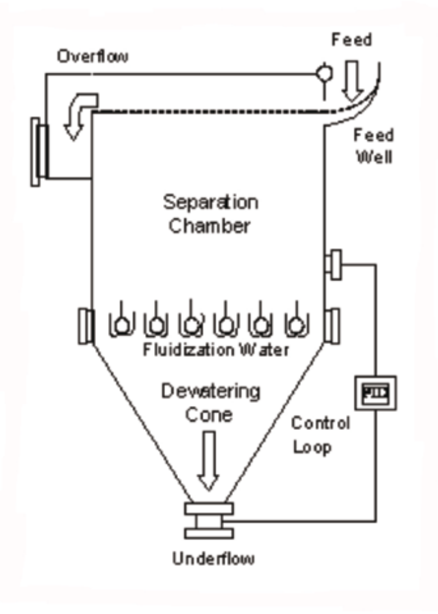

Figure 9. Schematic diagram of the CrossFlow hydraulic separator.

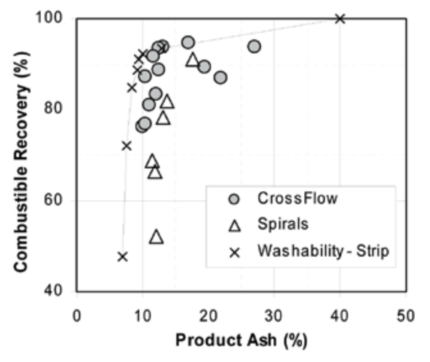

Figure 10. Pilot-Scale results versus washability. Comparison of the CrossFlow separator to spiral concentrators.

Wet drum magnetic separators - performance

Extensive sampling of wet drum magnetic separators in heavy media applications has indicated that the industry standard for magnetite losses is 0.25 g of magnetite/l of non-magnetic product. Figure 8 demonstrates the typical performance of a wet drum magnetic separator operating in a coal preparation plant employing a heavy media circuit. The wet drum magnetic separator was 0.9 m diameter with a counter-rotation style tank. This separator was isolated in the dilute heavy media circuit. The feed rate was incrementally increased with samples of the non-magnetic product taken at each level. The magnetite level was measured in each non-magnetic product sample.

CrossFlow hydraulic separator

Hydraulic separators are frequently used in the minerals processing industry to classify fine particles according to size, shape or density. Although many types of hydraulic separators exist, a device that has been gaining popularity in recent years is the teeter-bed or hindered-bed separator. The Eriez CrossFlow separator has been developed as a new generation of teeter-bed separator. It incorporates several 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 9.

Conventional hydraulic teeter-bed separators inject feed slurry directly into the teeter-bed. This causes turbulence in the separation zone resulting in a detrimental impact on separator performance. The CrossFlow design uses an improved feed delivery system that gently introduces the feed slurry across the top of the separator. This transitional feed system delivers the flow to the full width of the separator so that the slurry velocity, and any associated turbulence, is minimised. This feed system also minimises the effect of feed variations and allows for a constant teeter-water velocity throughout the separator.

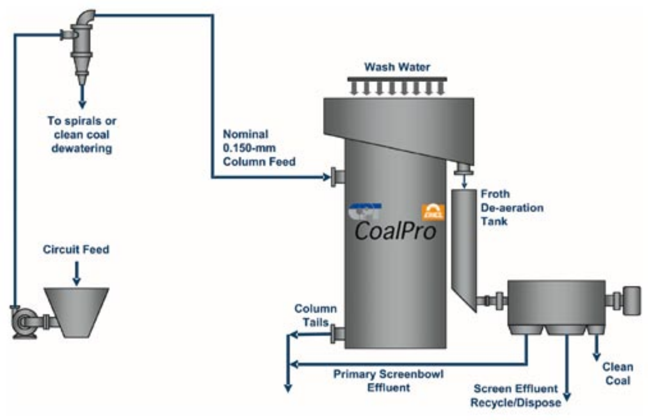

Figure 14. Traditional column flotation circuit treating by-zero coal. The feed to the column is typically -0.150 mm (-100 mesh).

CrossFlow separator - comparison testing

Central Appalachia strip coal

Test work was conducted using a pilot-scale CrossFlow separator to treat coal from a US strip operation. The material treated was relatively high in rock with a feed grade of approximately 40% ash. Operating in parallel with the CrossFlow was a single re-pulping test spiral. Feed was supplied to both units from an existing slurry distributor. Tests were conducted to create grade/recovery curves. The resultant data is presented in Figure 10. As shown, the CrossFlow separator operates very close to the washability curve. At maximum separation efficiency, a product containing 12% ash was produced at a mass yield of 78% and combustible recovery of 92%. In contrast, the spiral operated further from the washability data, providing a significantly higher ash product for the same combustible recovery.

While spirals offer many advantages, including high combustible recovery, they often suffer from misplacement of coarse rock to the clean coal product, as illustrated by the higher spiral product ash values presented in Figure 10. Additionally, coal spirals typically operate at a high specific gravity cut point.

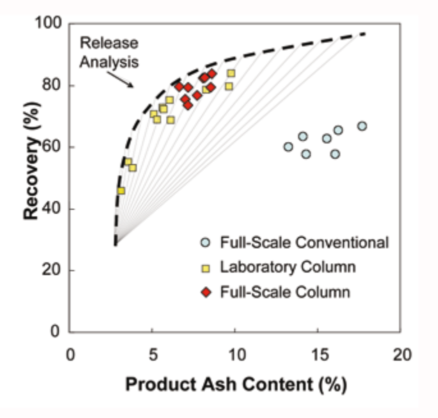

Figure 13. Comparison of column flotation cell results to a conventional mechanical flotation cell.

Table 1. Wet drum magnetic separator sizing parameters for heavy media application. Counter-rotation style tank. Heavy media sized (Grade E) magnetite. Feed slurry at less than 15% solids as magnetite.

Drum diameter	Sizing parameter	
	Hydraulic	Magnetic loading
0.9 m 36 in.	90 m^3/hr/m drum 120 gpm/ft drum	16 million tph/m drum 5.5 tph/ft drum
1.2 m 48 in.	130 m^3/hr/m drum 170 gpm/ft drum	28 million tph/m drum 9 tph/ft drum

CrossFlow separator - production scale

Southeast Appalachian coal

A full-scale CrossFlow was installed and commissioned at a Kentucky coal preparation plant. Performance data is presented in Figure 11. The unit worked well upon start-up and produced a clean coal product with an ash content of approximately 10%. This was achieved at a combustible recovery of better than 90%.

Three site evaluations were conducted in an effort to optimise separator performance. During the initial test period (set 1), the separator was simply sampled throughout the test period. Figure 11 shows that the combustible recovery regularly exceeded 90% with product ash values ranging between 8% and 10%. During a subsequent effort (set 2), the objective was to improve recovery while maintaining product grade. Evaluations were conducted while running the unit at a high bed pressure while varying the elutriation water rate.

Test set 2 resulted in an incremental improvement in combustible recovery as presented in Figure 11. The average combustible recovery and yield improved by nearly 2%. The data set generated during this follow-up testing suggested that additional performance improvement could be realised by further increasing the bed pressure. Generally, an increase in teeter-bed level will increase the effective gravity cut-point of the separator, thereby increasing combustible recovery.

This approach was investigated in a third test (set 3). Again, as seen in Figure 11, the increase in bed density improved the combustible recovery by an additional 2%. In total, this systematic approach resulted in an average increase in product mass yield of over 4% or 5.4 short tph (5.9 tph). For this installation, this process improvement resulted in a revenue increase of more than US$ 2 million per year (5.4 short tph x 7000 hr/yr x US$ 55/t).

CrossFlow separator - parameters

CrossFlow separators are sized based on the feed solids rate. Capacity is generally rated as tph of feed per m^2 of cross-sectional area. Material in the 2 mm x 0.150 mm (10 x 100 mesh) size range provides excellent separation response. The typical capacity for coal cleaning is 20 to 30 tph feed/m^2 (2 to 3 tph/ft^2) of cross-sectional area. CrossFlow separators have been manufactured up to 3 m^2. Typically a 3 m^2 CrossFlow separator can treat 180 to 270 tph of feed.

Column flotation

Recovering coal fines has typically been considered problematic due to high processing costs and poor flotation performance. However, the economical potential for fine coal recovery circuits continues to grow as the value of coal continues to climb.

Traditionally fine coal flotation has been conducted utilising conventional mechanical cells. These cells typically have a low profile and are arranged in series as a 'bank'. While conventional flotation cells are well-proven and are used extensively throughout the minerals industry, their primary drawback for coal recovery is the appearance of fine clay in the clean coal product. In contrast to a conventional mechanical cell, column cells utilise an effective method of froth washing. This approach virtually eliminates the hydraulic entrainment of clays resulting in high combustible recovery while maintaining maximum product grades.

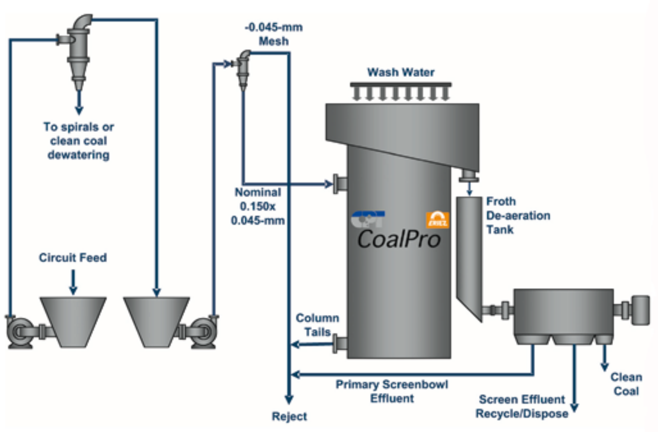

Figure 15. Deslime column flotation circuit with additional classification. The feed to the column is typically -0.150 mm + 0.045 mm (-100 mesh +325 mesh).

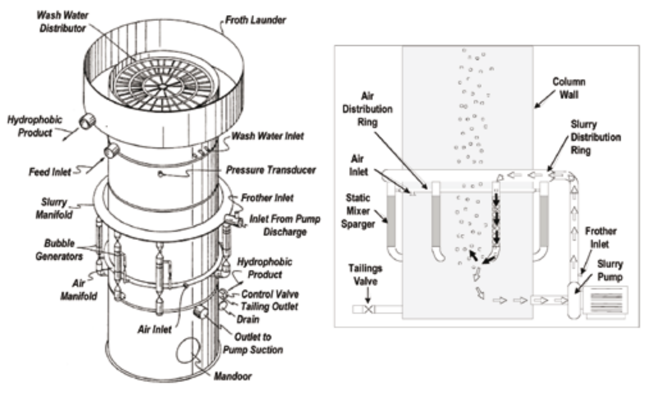

Figure 16. Microcel sparging system with essential design features.

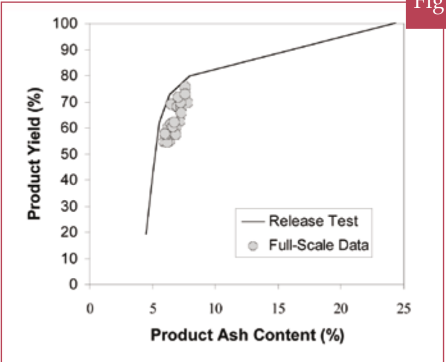

Figure 17. Typical plant performance compared to release analysis (by-zero circuit).

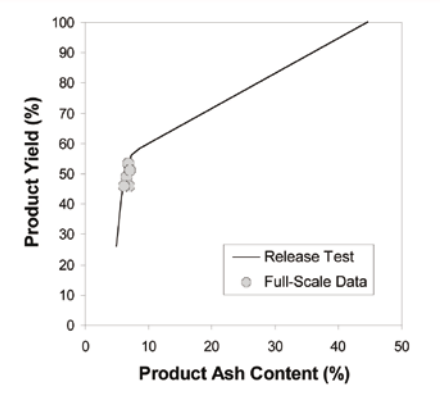

Figure 18. Plant performance compared to release testing (deslime circuit).

Column flotation - description

Unlike a conventional mechanical cell, feed slurry enters a column cell and is distributed throughout the cross-section of the cell. In the column cell, the slurry moves counter-current to a rising swarm of fine bubbles that are generated by an air sparging device. Particles that attach to the bubbles are carried up the column and are discharged to the product launder. Particles that do not attach settle down through the column and report to the underflow tailings stream. The additional benefit of column flotation is the ability to apply wash water to the froth column and eliminate clays from the product stream. An example of an industrial-scale froth washing system is presented in Figure 12.

The primary advantage of column flotation cells is the ability to provide a superior separation performance compared to conventional flotation processes. This capability can be easily illustrated by the test data summarised in Figure 13, which compares the column flotation technology with an existing bank of conventional cells. The data for the column cells tend to fall just below the separation curve predicted by release analysis which is an indication of the ultimate flotation performance for a given coal. In addition, the data from both a laboratory (5 cm diameter) test column and a full scale (3 m diameter) column fall along nearly identical recovery-grade curves. This finding suggests that the recovery-grade response obtained using small test columns can be used to confidently predict the performance of full-scale columns.

Column flotation - circuit types

There are two circuits commonly utilised for fine coal flotation. This includes 1) the traditional 'by-zero' circuit treating minus 0.150 mm (-100 mesh) feed material and 2) the 'deslime' circuit treating nominally 0.150 x 0.045 mm (100 x 325 mesh) feed material.

In the by-zero approach, minus 1 mm feed is sent to large diameter classifying cyclones. Typically, these cyclones are configured to make a cut-point of approximately 0.150 mm (100 mesh). This circuit is illustrated in Figure 14. The overflow stream of the cyclone is sent directly to flotation.

The second type of circuit, which has been gaining popularity, especially when producing coal for the steam market, is the 'deslime' circuit. In this circuit, a secondary bank of 150 mm (6 in.) cyclones is used to further classify the flotation feed at approximately 0.045 mm (325 mesh) in an effort to reject a large portion of the ultra-fine clay and/or coal particles. This circuit is illustrated in Figure 15. This approach can be advantageous when the feed stock contains little combustible material in the finest size classes.

Each circuit has certain advantages. The by-zero circuit will always provide the maximum product tonnes. On the other hand, the deslime circuit has continued to gain popularity due to its simplicity and ease of operation. In addition, the removal of the ultra-fine material results in a higher flotation capacity, reduces the number and/or size of columns required, and yields a product with lower moisture.

The ability to consistently maintain a high level of performance in a column flotation cell is a result of a relatively deep froth and efficient froth washing. Column systems must also maximise the rate of bubble surface area moving through the column in order to provide sufficient capacity. As such, the air sparging system is perhaps the most important component in a column flotation cell. Details related to the specific design features of various air induction and sparging technologies have been presented in the literature. The sparging systems recommended by Eriez are presented as follows.

SlamJet Sparger technology

Two different air induction systems are used in the Eriez CoalPro column flotation cells. One system is the Canadian Process Technologies SlamJet. The other is the Microcel.


Figure 19. 4.9 m (16 ft) diameter by 12.8 m (42 ft) tall column flotation cells with froth product shown (inset).

The SlamJet sparger system uses a series of removable air-lances which include a large, single orifice located at the end of the sparger. High velocity air is injected into the column cell to create and disperse fine bubbles. This technology incorporates a self-closing mechanism that eliminates the chances of back-flow of slurry into the aeration system. The SlamJet technology is best applied on deslime applications. This is due to the high aeration rates and slightly larger bubble size afforded by this bubble generation approach.

Microcel technology

Perhaps the most common sparging technology used in the coal industry is the Microcel system. This technology was conceived after research showed that the rate of flotation could be enhanced through the use of smaller air bubbles. The small (<0.8 mm) bubbles are generated by circulating slurry from the column through parallel in-line static mixers into which compressed air is injected. The design features of a CoalPro column flotation cell with the Microcel sparging technology are illustrated in Figure 16.

The Microcel sparging system has been best applied on by-zero or traditional fine coal recovery circuits. The primary reason is that the Microcel sparging system has the ability to efficiently generate large amounts of very small bubbles for a given airflow.

Column flotation cell parameters

Column flotation cells are sized based on the carrying capacity of the froth. The carrying capacity is the amount of coal product that the froth removes and is measured as tph of product per m^2 of cell cross-sectional surface area. The typical carrying capacity ranges from 1 to 3 tph/m^2 (0.1 to 0.3 tph/ft^2) and is highly dependent on the product particle size distribution. Column flotation cells have been manufactured up to 4.9 m (16 ft) in diameter and up to 16.0 m (52 ft) in height. Typically a 4.6 m (15 ft) diameter column flotation cell can produce 18 to 50 tph of flotation concentrate.

Column flotation - typical operating results

Results from a 0.150 mm x 0 (100 mesh x 0) operating flotation circuit are provided in Figure 17 plotted alongside earlier laboratory release analysis data. In this application, a maximum product yield of approximately 70% - 80% is achieved at an average ash content of 6% - 7%. Comparison to the laboratory release analysis results shows that a properly designed column circuit can eliminate non-selective entrainment.

Results from a 0.0150 x 0.045 mm (100 x 325 mesh) deslime operation is provided in Figure 18. For this operation, a maximum product yield of 55% is achieved at a product ash content of approximately 8%.

To date, 65 production scale CoalPro column flotation cells are in operation. Column flotation cells 4.9 m (16 ft) diameter by 12.8 m (42 ft) are shown in Figure 19.

Summary

Over the years, Eriez process equipment has evolved under the assessment of plant operation and performance. There have been new developments in process equipment resulting in an increase in coal recovery as well as providing a high level of productivity. Major improvements continue in essentially all areas of the equipment either focused on the separation or the ease of operation and maintenance.