THE APPLICATION OF THE STACKCELL TECHNOLOGY FOR FINE COAL RECOVERY

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ABSTRACT

The StackCell was developed to overcome the engineering and design challenges that are commonly associated with existing flotation technology such as pneumatic, self-aspirating cells, mechanical cells, and flotation columns. These challenges include high energy consumption, large floor-space requirements, and size. They are most evident when designing systems to process streams containing a high volumetric flow rate coupled with a significant float yield. Unlike many metalliferous and industrial mineral applications, fine coal flotation circuits are typically characterized by feed streams containing a low solids content (<5%, by weight) where up to 85% of the feed can report to the product launder. With input from major engineering houses and end-users, the Eriez Flotation Division (EFD) developed the StackCell technology with the goal of providing an additional flotation option for end-users. This technology was designed specifically to overcome these challenges by providing an efficient method of separation in terms of metallurgy, but also with respect to equipment size, energy consumption, and installed costs. Besides being placed in tandem with existing cells to provide cost-effective supplemental capacity, this technology can be installed in a stand-alone arrangement as recently demonstrated at Patriot Coal's Kanawha Eagle preparation plant. This manuscript provides an understanding of the underlying fundamentals of this new technology and presents data from Kanawha Eagle in addition to other industrial-scale installations.

KEYWORDS

StackCell, Flotation, Energy, Efficiency, Coal

INTRODUCTION

Over the past decade, column flotation has continued to gain acceptance as an alternative method for recovering fine coal due to superior metallurgical performance as compared to mechanical flotation cells. This point has been proven on numerous occasions by comparison of plant flotation data with the release analysis separation curve (Dell et al., 1972). Data from a release analysis test approximates the ultimate flotation response of a coal sample. In North America, a number of investigations have been published that document bottom-line improvements achieved using column cells (Luttrell et al., 1999; Kohmuench et al., 2004; Baumgarth et al., 2005). According to these reports, the benefits are derived from an overall increase in plant yield that can be achieved due to the improved product grade in the flotation circuit. In particular, the application of wash water to a deep froth utilized in column flotation minimizes the nonselective recovery of high-ash ultrafines that are hydraulically entrained in the froth by conventional flotation machines.

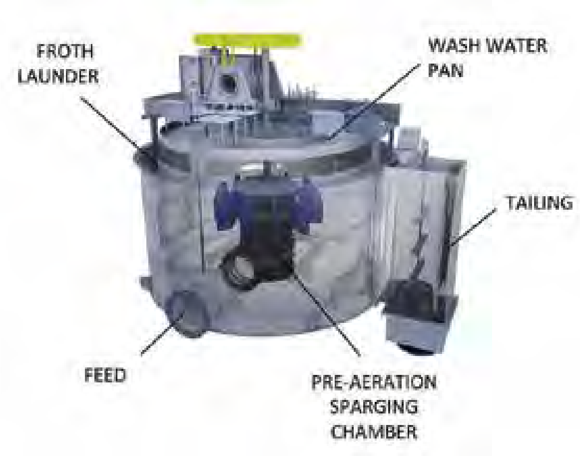

FIGURE 1
Three-dimensional rendering of a StackCell module

While column flotation offers substantially improved performance, there are design matters that must be considered for a properly engineered installation. One such challenge results from the aspect ratio of the cell itself. A column must be tall to achieve the desired residence time and minimize internal mixing conditions that are detrimental to cell performance. This design minimizes plant floor space requirements, but increases foundation loads. The column launder discharge must also be at a sufficient elevation to ensure that the froth can be properly conveyed to downstream unit operations (i.e., dewatering) and ultimately to the clean coal product belt. As a result, the column base is typically elevated resulting in additional structural steel to support this load.

Fabrication and erection also present challenges due to the large diameter of the cells. Economics associated with plant design typically lean toward fewer, large-diameter cells. To date, the largest columns installed in the U.S. coal industry are 4.9-meter (16-ft) diameter. While fabrication and operation of larger cells is routinely achieved in other applications and locations, the North American coal market is typically limited by equipment transportation issues. A 4.6-meter (15-ft) diameter column is the largest size that can be shipped as a single piece without vertical splices. Larger cells have been successfully designed and installed; however, these are supplied in multiple pieces and require significantly more on-site assembly. Additionally, larger diameter cells must also be taller to maintain the correct aspect ratio, which again, exacerbates the foundation and layout issues.

THE STACKCELL™ TECHNOLOGY

The concerns outlined above illustrate the need for the development of a new generation of flotation machine that offers column-like performance, while improving upon the design and operational challenges of traditional flotation circuits. Based on the experience gained over the last decade with the design, engineering, and operation of coal flotation circuits, Eriez has developed a new flotation cell that offers high capacity, a reduction in both size and horsepower, and superior metallurgical performance. This leap in technology is based on the application of flotation fundamentals. While column cells are still required for various applications, this new approach offers a flotation alternative that provides column-like performance with reduced capital, installation, and operating costs.

Figure 1 provides a 3D rendering of a single-stage StackCell machine. During operation, feed slurry enters the separator through either a bottom- or side-mounted feed nozzle at which point low pressure air is added. The feed can be introduced to the separator using a pump or via gravity. The slurry travels into an internal pre-aeration sparging device that provides significant shear and contacting prior to arrival into the separation chamber. In fact, all of the necessary bubble-particle contacting is conducted in an aeration chamber prior to injection into the primary tank which is used only for the phase separation between the pulp and the froth. A liquid slurry level is maintained inside the tank so as to provide a deep froth that can be washed, thereby providing a high-grade float product. Froth is then carried into the froth launder via mass action. These separators are specifically designed to have both a small footprint and operate with a gravity-driven feed system that allows cells to be easily "stacked" in-series or placed ahead of existing conventional or column flotation cells. As such, the StackCell successfully integrates key design characteristics of both traditional column flotation and conventional (mechanical) cells.

A unique feature of the StackCell is the method of sparging which utilizes a high-shear, bubble-particle contactor in lieu of the conventional rotor-stator mechanism historically utilized in mechanical float cells. Instead of operating with a large tank volume, the StackCell forces the bubbles and particles to contact within a very small confined area within an aeration chamber. Under this highly turbulent environment, the flotation rate constant (k) can be expressed as

$$k \propto C_b \, C_p \, E \qquad [1]$$

where C_b is the concentration of bubbles, C_p is the concentration of particles, and E is the specific energy imparted to the system (Williams and Crane, 1983). The high-shear environment within the aeration chamber provides an energy dissipation level that is substantially higher than that produced by conventional flotation machines, thereby enhancing the recovery of difficult-to-float particles. The contactor is specially designed to efficiently impart energy for bubble-particle contacting and to avoid unnecessary pumping or unwanted recirculation of the feed slurry. This allows the input energy to be used for gas dispersion and contacting and not for particle suspension. Moreover, the intense mixing shears the low-pressure air blown into the machine into extremely small bubbles, which substantially increases the concentration of bubbles present in the contacting chamber. This feed pre-aeration approach ensures that the maximum concentration of floatable particles and gas bubbles are present during the high-shear contacting.

The importance of this approach can only be appreciated after inspection of Equation 2 which shows the relationship of flotation recovery with the reaction rate, retention time and mixing conditions. The relationship is summarized as follows:

$$R \propto k \, \tau \, Pe \qquad [2]$$

where k is the reaction rate, τ is the retention time, and Pe is the Peclet number which quantifies the extent of axial mixing within the tank (Levenspiel, 1972). A higher value of Pe represents a more quiescent condition and improved recovery. According to Equation 2, the high rate constant (k) created by the high-shear environment within the aeration chamber allows the StackCell to operate at a correspondingly lower residence time (τ) without adversely impacting the recovery. Field studies conducted with a pilot-scale unit showed that a residence time of less than 10 seconds was often adequate for good contacting when using the StackCell technology.

This device can be theoretically applied to any system where differences in floatability between particles can be exploited. This technology successfully integrates the most important design characteristics of both traditional column flotation and conventional, mechanical cells. While details regarding these design characteristics and how they apply to flotation fundamentals are offered elsewhere (Kohmuench et al., 2008), a summary of the benefits afforded by this technology is provided below and include:

Small Cell Volume: As described above, the required cell volume for a StackCell installation is significantly less than traditional approaches. Therefore, both equipment and installation costs are reduced as a result of the "forced" pre-aeration approach that is carried out in the high-enery aeration chamber where both bubble and particle concentration are maximized.

Cell-to-Cell Configuration: Fundamental analysis by Levenspiel (1972) shows that in-series circuitry has an inherent advantage over parallel circuitry in that this approach minimizes short-circuiting that can occur if flotation cells are not designed properly. Follow-up studies by Stanley et al. (2006) successfully demonstrated this approach on a full-scale basis. The modular design of the StackCell allows for an in-series configuration to take advantage of improved mixing conditions. Field data suggest that three to four cells are required for most coal applications.

Column-Like Performance: The low-profile design of the StackCell achieves the flotation performance as predicted by release analysis by utilizing a highly efficient aeration system coupled with a deep froth. The high-grade float product is a result of the efficient displacement of feed slurry from the froth which minimizes entrainment. In the case of the StackCell, this is achieved by using an overhead, annular tray to evenly distribute wash water over a deep froth zone.

High Cell Surface Area: Similar to column flotation cells, the solids throughput of a flotation device is controlled by the froth carrying capacity (tons per hour per unit area). Limits on froth carrying capacity dictate that the system, regardless of cell type, must have sufficient cross-sectional area for each ton of coal recovered. The StackCell provides for this criterion by utilizing multiple cells. Given the smaller volume required, the diameter of each cell in a mulit-stage arrangement can be reduced, provided that the total surface area of the entire circuit is sufficient to carry the expected product load.

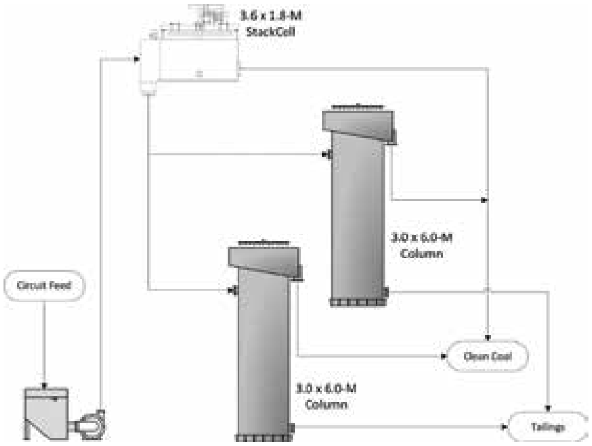

FIGURE 2
Generalized flow sheet of Roxana coal flotation circuit with StackCell as rougher unit

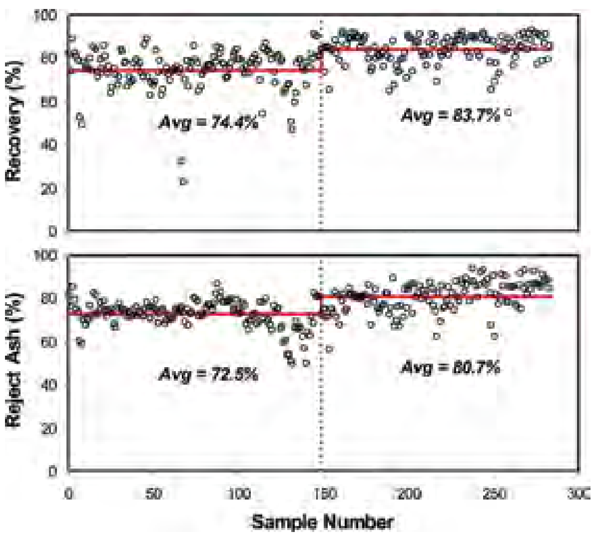

FIGURE 3
Change in flotation circuit performance after the installation of a StackCell with dashed line representing time of changeover (Davis et al., 2011)

Low Energy Input: In conventional, mechanical flotation cells, a significant portion of the energy input is inefficiently used to maintain particles in suspension. In the StackCell, the energy input is significantly lower considering the energy is focused specifically on creating bubbles within the aeration chamber. In addition, the aeration chamber operates under a near-atmospheric pressure in a manner that removes the need for a compressor to overcome the hydrostatic or dynamic head. As a result, a low-pressure and maintenance-friendly blower can be used as opposed to a compressor.

Low Capital and Operating Costs: The obvious benefit of the above mentioned design criteria is the resultant low capital and operating costs. The efficient use of energy solely for bubble generation along with the absence of a compressor greatly reduces the power requirements. In addition, the reduction in cell size reduces the total equipment and installation costs. Structural steel requirements are significantly less due to the reduction in tank weight and live load. The overall space requirement is also reduced given that the stacked-cell design is half the volume of an equivalent column circuit. Transport and installation are simplified since the units can be shipped fully assembled and lifted into place complete and without field welding.

INDUSTRIAL EVALUATION

ROUGHER APPLICATION

In order to demonstrate the performance capabilities of the StackCell technology, a full-scale unit was installed and commissioned at an industrial coal preparation plant. The plant processes run-of-mine coals from several seams supplied by both underground and surface mines. The StackCell unit consisted of a single 3.7-m (12-ft) diameter cell equipped with a 76-cm (30-inch) diameter aeration chamber. The single StackCell was installed as a rougher unit ahead of two existing flotation columns as seen in Figure 2. Historical data suggested that the two column cells were often overloaded due to plant production demands and a recent drop in feed ash content. The tailings stream from the StackCell was equally split and fed to the two existing columns.

Figure 3 shows the impact of the StackCell installation on the combustible recovery and refuse ash for the entire flotation circuit. For the first 149 samples taken prior to the installation, the two column cells provided an average recovery of 74.4% and a combined refuse ash of 72.5%. After the installation, the combined recovery for the StackCell and two column cells improved to 83.7% and the refuse ash increased to 80.7%. The increased recovery is significant considering that less than 10% more cell volume was added to the circuit via the installation of the StackCell technology. In fact, the aeration chamber provided an additional residence time of only about 5-10 seconds to the total flotation circuit. More recently, the average monthly plant recoveries have increased to more than 90%, while the average monthly tailings ash values have increased to nearly 86%.

Close inspection of the test data indicates a gradual improvement in overall performance since the StackCell was installed. The continued improvement can be largely attributed to the optimization of operating variables such as reagent dosage, froth depth, aeration rate and wash water addition rate that has occurred over time as a result of

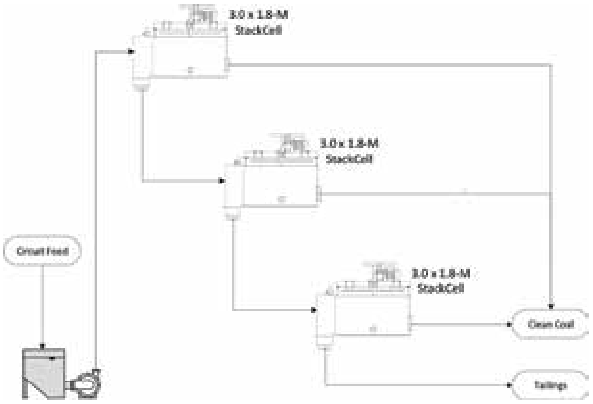

FIGURE 4
Gerneralized flow sheet for Patriot Coal's Kanawha Eagle floatation circuit

fine tuning by the plant operators. In fact, by using ample amounts of wash water, a recent test showed that the quality of the minus 45 micron clean coal product was reduced from just over 43.4% ash to under 13.3% ash. The plant data continue to show that the quality of the froth product is sensitive to froth depth and wash water addition. At optimal settings, the StackCell regularly achieves a product ash content ranging between 6.0% and 8.5%.

STAND ALONE, THREE-IN-SERIES APPLICATION

Given the success of the initial StackCell application, the Eriez Flotation Division worked with Patriot Coal, LLC to develop a coal flotation circuit that utilized three of these new units to be arranged in series for the Kanawha Eagle plant expansion. This multi-stage approach is similar to that used with conventional cells where each subsequent unit receives partially upgraded tailings from the previous machine. This arrangement provides higher recoveries for a given operating condition since the "cell-to-cell" circuitry reduces unwanted short-circuiting of feed to tailings. Recent studies by Stanley et al. (2006) successfully demonstrated the advantages of cell-to-cell circuitry for full-scale column flotation plants. Unfortunately, cell-to-cell circuitry is difficult to apply for columns due to their tall aspect ratio and large volumetric footprint. On the other hand, the modular design of the StackCell easily accommodates the in-series configuration to take advantage of improved mixing conditions so long as sufficient cell surface area is provided in order to achieve the needed product carrying capacity. Therefore, as shown in Figure 4, the preferred arrangement for this application was to employ three sequential stages of StackCells.

The Kanawha Eagle flotation circuit was engineered to treat up to 55 t/hr of minus 0.150-mm fine coal at nearly 800 m^3/hr. The first cell is designed to recover the most coal given that the material with the higher flotation rate will quickly report to the product launder. The subsequent cells act as scavenger units that capture any remaining, slower floating coal. Frother and collector are added into the feed sump and also as required between cells in order to maintain froth stability and combustible recovery. A deep froth (>450 mm) is maintained on each cell while wash water is added to ensure a high-quality product. Due to the circuit arrangement prior to the expansion, the first StackCell is pump fed, but the flow between cells is via gravity.

Provided in Table 1 are the circuit design data along with the expected metallurgical results that were based on the limited preliminary flotation data available prior to the expansion. Also included in this table are the actual metallurgical results after initial optimization. It should be noted that optimization of the circuit is not yet complete and that improvements are continuously being realized as the circuit is examined in greater detail. For instance, very little collector (i.e., diesel) was utilized during start-up and commissioning of the circuit. In addition, the collector was added just prior to the StackCells and not into the flotation feed sump which would provide additional conditioning time. Frother addition rates were also very lean and on the order of 7-9 ppm whereas the recommended range for a glycol-based frother is 10-14 ppm and required to provide a sufficiently stable froth for washing.

	Design	Actual
Feed Tonnage (t/hr)	55	72-82
Feed Rate (m^3/hr)	800	800
Feed Solids (%, by weight)	6.7	8.9
Feed Ash (%, dry)	45.3	50-53
Product Tonnage (t/hr)	29.8	28-30
Product Solids (%, by weight)	10.4	13-14
Tailings Ash (%, dry)	81.2	79.2
Circuit Yield (%)	49.7	31-38
Product Capacity (t/hr/m^2)	1.26	1.19-1.29
Circuit Comb. Recovery (%)	81.2	72.4

TABLE 1
Design and actual metallugical data from the Kanawha Eagle StackCell installation

Circuit Variable	Stack Cell	Column	Combination	
	SC-3050	Cav-Tube	SC-3050	Cav-Tube
Cell Diameter (m)	3.00	4.25	3.00	4.25
Cell (No.)	4	4	2	2
Circulation Pump	—	✓	—	✓
Blower	✓	—	✓	—
Compressor	—	✓	—	✓
Total Connected Power (HP)	840	1600	1110	
Live Load (kilotonne)	404	1140	671	
Est. Equipment Cost (US$)	$1.5M	$1.5M	$1.2M	

TABLE 2
Various floatation options for 70 t/hr flotation by-zero circuit with 80% float yield

In spite of the circuit deficiencies, the 3-stage StackCell arrangment is achieving metallurgical results close to that of design. While the feed flow rate to the circuit is as expected, the actual tonnage that is being processed through the flotation circuit is significantly higher at an average of 77.0 t/hr versus the design of 55.0 t/hr. However, the feed ash to the flotation circuit is also much higher at an average of 51.5% ash versus the expected ash content of 45.3%. The data show that the StackCell circuit is able to recover 30 t/hr of product at a solids content of 13% to 14%, by weight. This compares well with the expected rate of 29.8 t/hr at a solids content of 10.4%. Combustible recovery for the circuit is nearly 73% with a tailings ash content of 79.2%. While the combustible recovery is not as high as indicated by the design, the product carrying capacity is as expected as indicated by the overall product tonnage.

SIMPLE ECONOMIC EXAMPLE OF INDUSTRIAL APPLICATION

The decision of when to use StackCells and/or columns is based on both economics and coal characterization data. Since the retention time in the StackCell is limited, it is best used for treating coal stocks that have relatively high rate constants. For a mix of material, it may be best to utilize a combination of StackCells and columns much like the "rougher" example above. In this arrangement, the StackCell can recover the faster floating material while the secondary column recovers the remaining slower floating coal as a result of the increased retention time.

A recent in-house exercise indicated that for a 70 t/hr flotation circuit (0.150-mm x 0), four StackCells placed in-series are needed to meet the carrying-capacity requirements for a fine metallurgical coal. In comparison, a hybrid circuit that utilized StackCells followed by column flotation cells yielded a capital cost savings of 20% as seen in Table 2 when also considering the cost of the ancillary equipment such as pumps, compressors, and blowers. Of course, this capital cost savings must be weighed against the savings generated by the smaller footprint and weight offered by the StackCells. Regardless, in this exercise, a hybrid circuit incorporating both StackCells and columns offered an optimized solution that provided both capital and operational cost savings while ensuring good metallurgical performance through the in-series arrangement that combined the benefits of pre-aeration and increased retention time.

SUMMARY

A new high-capacity flotation technology, the StackCell, has been developed as an alternative to both conventional and column flotation machines. This technology makes use of a pre-aerated, high-shear feed canister that provides efficient bubble-particle contacting, thereby substantially shortening the residence time required for coal flotation. Other potential advantages of the process include low air pressure requirements, low capital and installation costs, and increased flexibility in plant retrofit applications.

Recent full-scale plant trials suggest that this low-profile technology can provide coal recoveries and product qualities comparable to column flotation systems. Two full-scale approaches were tested including a single unit rougher application as well as a 3-stage, in-series arrangement. In the rougher application, the StackCell was able to successfully offload an existing overloaded flotation circuit which resulted in an increase in combustible recovery in excess of 90%. For the 3-stage circuit, the metallurgical results show that the StackCells, when arranged in-series, are meeting the design requirements at an acceptable combustible recovery, product carrying capacity, and product ash content.

While it is not expected that this new technology will replace the need for column flotation, it does provide an alternate means to efficiently achieve column-like performance when plant space and/or capital is limited. In particular, the small size and low weight of this new technology makes it amenable to low-cost plant upgrades where a single unit can be placed into a currently overloaded flotation circuit with minimal retrofit costs.

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