Enhanced Gravity Separators:
New Alternatives for Fine Coal Cleaning

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ABSTRACT

A new generation of centrifugal enhanced gravity separators is now available for fine coal cleaning. Commercially available units include the Falcon Concentrator, Kelsey Jig, Knelson Concentrator and Mozley Multi-Gravity Separator. These devices, which were originally developed in the minerals processing industry, are capable of upgrading particles once believed to be too fine for water-based gravity separators. In the case of coal, efficient separations have been achieved down to particle sizes of 325 mesh and finer. These units are particularly well-suited for pyritic sulfur removal because of the large density difference between pyrite and coal. This article describes the basic working principles of this new generation of gravity separators and provides a review of the advantages and limitations of each for fine coal processing. Topics addressed in this article include separation performance, unit capacity, and process economics.

INTRODUCTION

Surface-based separation processes such as froth flotation and oil agglomeration have been traditionally recognized as the only practical methods for cleaning fine coal (i.e. 100 mesh x 0). These processes are very selective in rejecting well-liberated mineral matter, but are much less effective if the feed coal contains a disproportionate amount of composite particles (i.e., middlings). The separation can be further complicated by the fact that pyrite can become floatable if the surface chemistry of the flotation pulp is not properly controlled. Unfortunately, the problems associated with the use of froth flotation for treating coal fines are expected to increase as reserves of easily cleaned "black-and-white" coals diminish and the incentives for improving coal desulfurization grow.

Investigations conducted during the past several years suggest that the problems associated with surface-based separation processes such as froth flotation may be overcome using on of several enhanced gravity separators recently developed in the mineral processing industry. Notable examples of the units include the Falcon Concentrator, Kelsey Jig, Knelson Concentrator and Mozley Multi-Gravity Separator. All of these units are water-based devices which use centrifugal forces to improve the separation of fine particles based on differences in density. Several laboratory and pilot-scale units have already been tested for the upgrading of fine coal. Although most of the preliminary test results are very promising, no commercial-scale units have been installed in the coal industry to date.

This article provides a review of some of the recent test data obtained for coal applications using this new generation of centrifugal water-based separators. The article describes the basic operating principles of the various separator designs and points out some of the advantages and limitations associated with the novel features of each design. Major items to be addressed include separation performance, unit capacity and process economics.

BACKGROUND

Fundamental studies conducted at Virginia Tech (Adel et al., 1991) suggest that density-based separation processes are fundamentally superior to surface-based processes for the upgrading of fine coal. For example, a composite particle containing 80% coal and 20% pyrite by volume would have a very high probability of being recovered by froth flotation. This is due to the large amount of coal surface area exposed to the air bubbles in the flotation pulp. In fact, recent studies suggest that composite particles containing as little as 5-10% coal often report to the clean coal product in industrial flotation banks. On the other hand, the 20/80 particle of pyrite-coal would have a specific gravity of 2 and would be easily rejected by an efficient density-based coal cleaning process. Unfortunately, conventional density-based separation processes are incapable of effectively upgrading fine coal.

The problem of treating very fine particles by density-based separation processes is illustrated in Figure 1. This plot shows the theoretical settling velocity of spherical particles of pure coal, shale and pyrite having specific gravities of 1.3, 2.5, and 4.8, respectively. The calculations were performed using well-known Stokes and Newton laws for free-settling conditions (McCabe and Smith, 1976). Two sets of calculations have been plotted, one under a normal gravitational field of 1 g (solid lines) and the second under an artificial gravitational field of 200 g's (dashed lines). As shown, the settling velocity of particles subjected to the normal gravitational field rise very rapidly above 1 mm. Since the gravitational force is proportional to particle mass, particles smaller than 1 mm separate slower, and hence less efficiently, than do particles in the larger size ranges. However, by applying an artificial gravitational field, particle settling velocities can be greatly enhanced and the effective size range over which efficient separations can be achieved can be extended to much smaller sizes. As shown in Figure 1, high settling velocities can be maintained down to 0.1 mm by applying an artificial gravitational field of 200 g's. The additional force will permit efficient separations to be achieved even at these very fine particle sizes. Details related to this phenomenon and their implication on particle separation have been previously discussed by Driessen (1945).

ENHANCED GRAVITY CONCENTRATORS

In order to take advantage of the efficiency improvements that may be realized by using artificial gravitational fields, anew generation of enhanced gravity separators have been developed and placed into commercial production in the minerals processing industry. Four of the most well-known of these units are described in the following sections.

Falcon Concentrator

The Falcon unit, which is essentially a centrifugal sluice, consists of a smooth-surface truncated cone which rotates at a very high speed (Figure 2a). Feed slurry is injected near the bottom of the cone and is accelerated up the cone wall by the centrifugal field (up to 300 g's). The slurry forms a thin flowing film in which particles become stratified based on differences in density. Light particles atop the stratified layer are discharged over the top of the cone lip, while heavy particles sliding along the inner surface of the cone are discharged through the cone wall via small reject ports. Falcon units are being used to upgrade a variety of minerals including base sulfides, iron, tin, titanium and gold ores. Pilot-scale units have recently been successfully demonstrated for the upgrading of 28 mesh x 0 coal fines (Honaker et al., 1994). Since the discharge rate is fixed under constant operating conditions, the use of this unit in the coal industry may be limited to coal feeds which have a relatively constant amount of reject. To overcome this limitation, a control system which regulates the discharge rate by varying the bowl speed has been suggested (Fonseca, 1994).

Kelsey Jig

The Kelsey jig consists of a series of hutches which are rotated about a central feed pipe (Figure 2b). The unit is capable of generating centrifugal fields up to 100 g's. A cylindrical screen is mounted across the top of each hutch to retain ragging material. Feed slurry enters the unit through the central feed pipe and flows outward across the bed of ragging. Mechanical pulsators located within each hutch create oscillations in the bed that differentially accelerate particles based on differences in density. Low-density particles flow across the ragging material and overflow the top of the unit, while high-density particles pass downward through the ragging/screen and are discharged through actuated valves. In most cases, the unit forms its own ragging material form coarser and heavier feed particles. The Kelsey jig has been successfully demonstrated for the concentration of tin, mineral sands, iron ore, gold, lead, manganese and platinum. It has also been tested in Australia for ash removal (Riley and Firth, 1993) and is currently marketed by GeoLogics Pty. Ltd. In Australia and in the U.S. by Eriez Magnetics. The need to constantly replenish the bed of ragging appears to be the major shortcoming of this particular design. However, narrowly sized clean-coal (1.2-2 mm) cycloned from coarse spiral products have been successfully used for this purpose (Merwin, 1994).

Knelson Concentrator

The Knelson separator consists of a rotating truncated cone which is stair-stepped by several ring-type partitions (Figure 2c). Feed slurry is injected through a central feed pipe and is allowed to flow countercurrent fashion from partition to partition until it overflows the top of the rotating bowl. Rinse water forced through perforations in the rotating bowl creates a fluidized bed of particles between each partition. Particles which have a density higher than that of the fluidized bed are collected behind the partitions, while lighter particles are flushed out over the partitions. Over 750 Knelson units have been sold in the minerals processing industry, and it is currently on e of the most widely used methods of recovering fine free-gold. More recently, a continuous flow Knelson unit was field tested at a coal preparation plant in central Australia and similar testing is planned at the Canadian Coal Research facility in Alberta (Knelson 1992). One of the major disadvantages of this unit is the large fresh water requirement (up to 2-3 times the feed flow) needed to fluidize the particle bed.

Mozley Multi-Gravity Separator

The operating principle of the MGS is similar to that of a conventional shaking table, except that centrifugal forces are used to enhance the separation of fine particles (Figure 2d). In this system, feed slurry is distributed along the inner surface of a slightly tapered rotating drum. Light particles are carried by the flowing film to the far end of the drum, while heavy particles pinned against the wall by the centrifugal field are carried by rotating scrapers to the opposite end of the drum. A small amount of wash water is added to the heavies discharge end of the drum to wash out entrained low-density particles. Successful applications of the MGS technology include the concentration of cassiterite, chromite, wolfamite, graphite, mixed sulfides and gold. In addition, testing of a pilot-scale MGS unit was recently completed at the Pittsburgh Energy Technology Center (PETC) for applications involving the desulfurization of fine coal (Contract No. DE-AC22092PC92205). The results of this work showed that the pyritic sulfur rejection obtained by the MGS was nearly twice that achieved using conventional fine particles processing techniques. Since the unit operates under a low centrifugal field (<25 g's) its throughput capacity is very low compared to the other enhanced gravity separators.

TEST RESULTS

Each of the enhanced gravity separators described in the previous sections have been evaluated on a limited-scale for applications involving coal. Examples of test results obtained with various coals are summarized in Table 1. The data were obtained using laboratory and pilot-scale test units. The results cannot be directly compared since different coal seams and size ranges were examined in each case. However, the results do suggest that the various units are capable of achieving good rejections of ash (>40%) and sulfur (>60%) at very good coal recoveries (>80%).

Table 1 – Typical test results obtained with various enhanced gravity separators.

Separator	Coal Sample (Size Range)	Combustible Recovery (%)	Ash Rejection (%)	Total Sulfur Rejection (%)
Falcon[1]	Illinois No.5 (65x400 mesh)	88.3	68.1	72.5
Kelsey Jig[2]	Wirringham (32x400 mesh)	96.9	43.6	-----
Knelson[1]	Illinois No.5 (65x400 mesh)	84.2	69.1	70.3
Mozley[3]	Pittsburgh No.8 (65 mesh x 0)	86.1	72.9	64.4

1- Paul et al, 1994; 2 - Riley and Firth, 1993; 3 – Venkatraman et al, 1995

The impact of particles size of the overall performance of the various test units is illustrated in Figures 3-5. The first plot (Figure 3) shows the test data obtained using a 10-inch diameter Falcon concentrator to process coal from the Illinois No. 5 seam. Although only three size fractions were examined in this series of tests, it is apparent that the weak performance for the unit was obtained for particles in the intermediate size range near 0.1 mm. The poorer rejections of ash and sulfur in the coarse size range may be attributed to the recovery of large particles of mineral matter which remain in the high-velocity region of the flowing film. In contest, the poorer performance observed in the fine size range (i.e., 325 mesh x 0) is most likely due to the presence of ultrafine clay "slimes" which are carried into the clean coal product by entrainment with the bulk of the liquid flow. The centrifugal force is simply too small to permit the recovery of clay particles which occur in the ultrafine size range. This conclusion is supported by additional test results which indicate that efficient separation can be maintained down to 0.01 mm (Honaker et al., 1995).

Size-by-size test results for a pilot-scale (0.2 tph) Kelsey jig are shown in Figure 4. The data were obtained using undeslimed fine coal from the Wittingham seam in Australia. The test results indicate that the performance of the Kelsey Jig is optimum when treating particles in the size range between 0.08 and 0.2 mm. The gradual decline in performance at coarser sizes has been attributed to problems associated with the passage of large amounts of coarse shale particles through the loosely-packed bed of ragging material which rests atop the cylindrical bowl screen (Riley et al., 1995). Various types of ragging material, including spherical glass beads, are being evaluated in an attempt to minimize this problem (Merwin, 1994). A expected, the centrifugal field generated by the Kelsey jig is also too small to effectively reject ultrafine clay slimes. In fact, tests conducted in Australia (Riley et al., 1995) has shown that essentially all of the material finer than approximately 400 mesh reports to the clean coal product via hydraulic carryover.

Figure 5 provides the test data obtained using the MGS as a function of particles size. As shown, the particles size range which can be effectively processed by this unit is essentially identical to that obtained using the Kelsey Jig. Operating experience suggests that very coarse particles of mineral matter which reside in the high velocity region of the flowing-film tend to be carried nonselectively into the clean coal product. Attempts to reject these particles by "pinning" them to the drum wall via increasing the speed of the rotating drum has the adverse impact of reducing coal recovery by pinning coarser coal particles as well. The MGS is also incapable of rejecting ultrafine clay slimes which report with the flowing-film to the clean coal product. Test results obtained to date suggest that the MGS may be marginally better than the Kelsey Jig in rejecting particles in the finer size range, although insufficient data exists at this time to validate or reject this observation.

Relatively little information is available regarding the size-by-size performance of the Knelson concentrator since this unit was only recently introduced to the coal industry. However, data obtained at Southern Illinois University (SIU) using an Illinois No. 5 seam coal suggest that this separator is capable of maintaining good recoveries (90%) and rejections of ahs (55%) and sulfur (45-55%) over the size range from 28 to 400 mesh. Although data is not yet available regarding the performance of the unit in treating 400 mesh x 0 material, it is expected to be subjected to the same limitations as the other enhanced gravity concentrators.

EFFICIENCY COMPARISONS

Figure 6 shows a comparison of the probable error (Ep) values obtained for the Falcon concentrator, Kelsey Jig and Multi-Gravity Separator over a wide range of particle sizes (Paul, 1994; Riley and Firth, 1995; Yoon et al., 1995). Performance data has not yet been reported for the Knelson unit. The data show that each of the units achieved an optimum Ep value (i.e., 0.1-0.2) in the size range between 0.1-0.3 mm. As expected, unit performance diminished in both the coarser and finer size ranges for reasons discussed previously. The decline in performance diminished in both the coarser and finer size ranges for reasons discussed previously. The decline in performance with decreasing particle size was most notable with the Kelsey jig and may be due to the relatively large flow of hutch water employed by the unit. In any case, Ep values obtained by these units are comparable to those obtained at much coarser sizes by spirals (Ep=0.12-0.2), shaking table (Ep=0.15-0.2) or water-only cyclones (Ep=0.2-0.25). These values are also far superior to the Ep value of 0.28 reported for the froth flotation process (Horsfall, 1989).

The impact of particle size on the specific gravity of separation (i.e., cut-point) is shown in Figure 7 for each of the various test units. With the exception of several of the data points reported for the Falcon concentrator, most of the data tended to fall at a cut-point between 1.9 and 2.1 SG. The lower cut-points reported for the Falcon unit were obtained at increasingly higher rotational speeds. In fact, the data shown in Figure 8 suggests that the effective specific gravity of separation can be decreased by increasing the strength of the centrifugal field. Thus, the high-speeds afforded by the design of the Falcon unit may provide it with an inherent advantage over the other units in terms of lower cut-points and higher capacities.

CAPACITY COMPARISONS

An overview of the rated capacities for the various enhanced gravity separators is provided in Table 2. For comparison, the capacities have been reported as tonnage of clean coal per unit of bowl/drum/screen surface area or per unit of bowl/drum/screen circumference. Only verified tph/ft and tph/ft^2 capacities obtained using pilot-scale test units have been reported. The data obtained to date suggests that the Kelsey Jig has the highest overall capacity, while the MGS has the poorest. However, the manufacturer of the Falcon unit claims that significant improvements in capacity are achieved during scale-up of Falcon concentrator. Thus, as shown in the last column of the table, the full-scale Falcon unit is reported to have a tremendous capacity advantage over the other separators. Experimental validation of the very high capacity of the full-scale Falcon unit is currently underway at the Southern Illinois University (SIU).

Table 2 – Estimated capacities and equipment costs for various enhanced gravity separators.

Separator	Approximate Capacity (tph/ft^2)	Approximate Capacity (tph/ft)	Estimated Capital Cost ($ U.S.)*
Falcon[1]	0.5-1.5	0.5-1.0	$200K for >50 tph
Kelsey Jig[2]	1.5-2.0	1.5-2.0	$150K for 5-15 tph
Knelson[1]	0.1-0.4	0.25-0.50	$150K for 20 tph
Mozley[3]	0.01-0.03	0.03-0.06	$200K for 5-15 tph

1- Paul et al, 1994; 2 - Riley and Firth, 1993; 3 – Venkatraman et al, 1995

* Costs estimated from verbal quotes and/or advertised materials and may be subject to considerable variations depending on market conditions.

SUMMARY

A survey of test results obtained during the past several years indicate that several of the enhanced gravity separators that were originally developed in the minerals processing industry may be useful for treating fine coal (i.e., 28 mesh x 0). The major advantage of the enhanced gravity concentrators appears to be their ability to reject composite particles more efficiently than flotation. In particular, particles containing a high specific gravity component such as pyrite are rejected very efficiently by this new generation of fine particle separators. Unfortunately, none of the units tested to date appear to be capable of handling ultrafine clay "slimes" which report with the clean coal by entrainment. Thus, the feed and/or product coals from these units may need to be deslimed in many cases to remove ultrafine ash-forming minerals. Small-diameter cyclones equipped with a water-injected apex may prove to be useful for this purpose. Froth flotation (particularly column flotation with its use of forth washing) also appears to be an attractive method for removing clay slimes either before or after treatment by the enhanced gravity separators.

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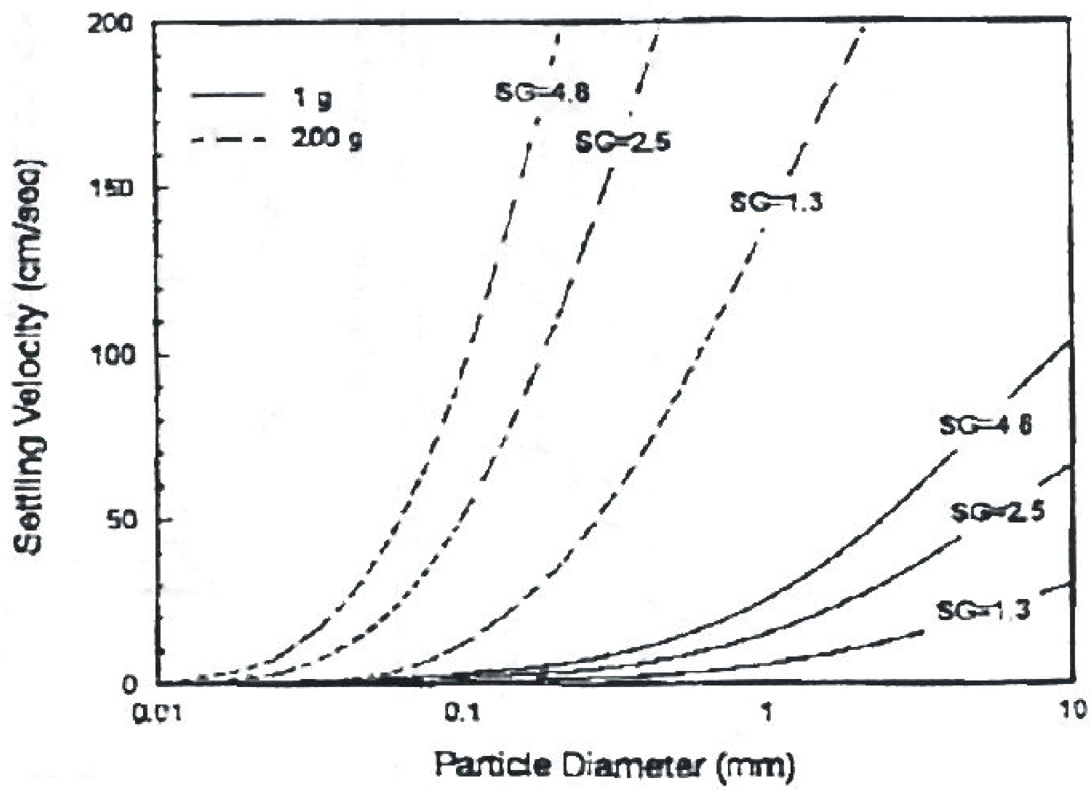

Figure 1 – Theoretical effect of particle diameter on the free-settling velocity of coal (SG=1.3), shale (SG=2.5) and pyrite (SG=4.8) under gravitational fields of 1 and 200 g's