Chapter 5

ENHANCED GRAVITY SEPARATION: AN ALTERNATIVE TO FLOTATION

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Abstract. Recent research has shown that froth flotation is not effective at treating fine coals (-28 mesh) containing a large portion of middling particles. Due to their relatively large density differences, middling particles can be separated more efficiently using gravity-based processes. The ability of gravity separators to treat fine particles has been limited by the lack of particle inertia relative to the surface drag forces. However, particle inertia can be enhanced by the application of a centrifugal field. A commercial-scale centrifugal Falcon concentrator capable of treating a mass flow rate of greater than 1 tph continuously has been used to evaluate its feasibility for treating fine coal as an alternative to froth flotation. Tests conducted on a -28 mesh fine coal circuit feed have found the Falcon concentrator to be very effective at cleaning the 28 x 325 mesh size fraction. For an Illinois No. 5 coal sample, the ash content was reduced in the 100 x 325 mesh size fraction from about 18% to 8% while achieving a high combustible recovery value of nearly 97%. In addition, the total sulfur content was substantially decreased from 2.6% to 1.7%. The effects of the critical operating parameters on separation performance have been studied and their values optimized.

INTRODUCTION

Froth flotation, a physico-chemical process, is the most commonly used process for treating fine coal, i.e., 28 mesh x 0. Since separation is achieved on the basis of surface hydrophobicity, mixed-phased particles or middlings are not efficiently treated by froth flotation. Middling particles containing as little as 5% coal may report to the froth concentrate due to bubble attachment to the coal portion that is exposed on the particles' surface. Another problem occurs when the coal pyrite is hydrophobic which results in a high recovery of sulfur components to the froth concentrate.

A possible solution to the shortcomings of the froth flotation process is the use of enhanced gravity separators. Numerous studies comparing washability curves to flotation results have found that density-based processes are always more efficient at treating coals containing a significant amount of middlings (Adel et al., 1991; Killmeyer et al., 1992). Enhanced gravity separators provide the centrifugal force needed to effectively treat fine coal particles (Han and Say, 1985).

The enhanced gravity concentrators that operate continuously and are commercially available include the Multi-Gravity Concentrator (MGS), the Kelsey Jig, the Knelson Concentrator, and the Falcon Concentrator. Initial studies using enhanced gravity separators for fine coal cleaning combined advanced froth flotation with the MGS unit for improved sulfur rejection (Luttrell et al., 1993). However, tests performed on the Kelsey Jig found that high ash rejections can also be achieved on fine coal using enhanced gravity separation (Riley and Firth, 1993). Work conducted at SIUC using a semi-batch Falcon concentrator also found that high ash and sulfur rejections can be achieved on 28 mesh by 10 µm coal size fraction (Honaker et al., 1994). This publication will present the findings obtained from the use of a continuous Falcon concentrator to treat fine coal circuit feed that is nominally 28 mesh x 0.

EXPERIMENTAL

Enhanced Gravity Concentrator

The enhanced gravity separator used in this investigation was a continuous Falcon Concentrator having a 0.25 m (10-in) diameter bowl. This concentrator utilizes up to 300 *g*'s of centrifugal force to cause deposition and stratification of the fine particles against the inside of a smooth centrifugal bowl. As shown in Figure 1, the feed is introduced at the bottom of the bowl and onto a spinning rotor. An impeller hurls the feed against the wall of the rotor. The bottom of the rotor is called the migration zone, and is inclined at a slight angle so that the enhanced gravity field generated by the spinning rotor can be resolved into two force components. The strong component normal to the wall is the concentrating gravity field that provides the strong *g*-forces for the hindered settling processes and stratification of the feed. The weak driving component parallel to the inclined rotor surface pushes the stratified solids up toward the top of the bowl.

The angle of incline on the rotor surface changes near the top of the rotor so that it is now parallel to the axis of rotation. As a result, there is no weak gravity force component to drive particles upward toward the top of the rotor. This part of the rotor is called the retention zone. Light particles on the outside of the bed move upward to the overflow lip of the rotor using the momentum

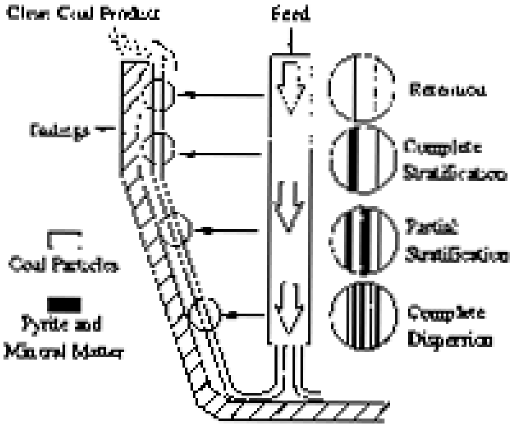


Figure 1. A schematic illustration of the operating principles of the continuous Falcon Concentrator.

they accumulated in the migration zone and the force of the upward flowing water film. Heavy particles and coarse, light particles form a bed on the bowl surface with the heavy particles forming a layer nearest the bowl wall. The bed of particles move along the bowl wall and across a 0.13 m (1/2-in) slot that exists around the circumference of the bowl. The heavies flow into the slot and are discharged using pinch valves. The light, coarse particles flow over top the slot and report to the overflow as the final product with the particles that remained dispersed in the feed water.

Test Sample

The coal sample used in most of the tests in this study was collected from the fine circuit stream (28 mesh x 0) of a coal preparation plant treating the Illinois (Herrin) No. 5 seam coal. A wet screening analysis revealed that 52.5% of the sample was +100 mesh, 17.6% was in the 100 x 325 mesh size fraction and 29.9% was -325 mesh. The size-by-size assays of the sample can be found in Tables 2 and 3 corresponding to the Illinois No. 5 (S2) sample. The original feed solids content of the stream was 18% by weight.

Experimental Procedure

Prior to each test, four 208 liter (55 gallon) drums of coal slurry were placed in a feed sump where the feed solids content was adjusted to the desired value. During the tests, the Falcon unit was fed from a split stream on a recirculation loop that transported material from the bottom of the feed sump to its top. The feed rate was adjusted using valves located on the recirculation line. The Falcon unit was mounted slightly above the feed sump so that the overflow (product) and underflow (tailings) streams could be gravity fed back into the feed sump. After allowing sufficient time for the process to reach steady-state, a timed-sample of the feed, product, and tailing streams were collected in short incremental time periods for approximately 5 minutes. The product and tailing samples were then wet screened into three size fractions, i.e., +100 mesh, 100 x 325 mesh, and -325 mesh.

RESULTS AND DISCUSSION

Parametric Study

An experimental program based on a Box-Behnken statistical design was conducted on the Falcon Concentrator to evaluate the effect of the operating parameter values on separation performance. The parameters and their respective values studied in the Box-Behnken design, which required a total of 27 tests, are shown in Table 1. The overflow and underflow samples were screened to obtain size-by-size results. The test data, which resulted from the treatment of the -28 mesh Illinois No. 5 coal sample, were used to develop empirical relationships describing the response variables (i.e., separation efficiency and total sulfur rejection) as a function of the operating parameter values. A quadratic model was found to provide the best fit for the experimental data and took the following form:

$$R.V. = k_1 + k_2(FR) + k_3(FS) + k_4(BS) + k_5(OT) + k_6(FR)^2 + \ldots + k_{15}(BS)(OT) \qquad [1]$$

where *R.V.* is the response variable, ***FR*** the volumetric feed rate, ***FS*** the feed solids content, ***BS*** the bowl speed, ***OT*** the opening time of the underflow pinch valve which controls the underflow rate, and k_i the parameter constants. The closing time for the underflow valves was kept constant at 4 seconds throughout the 27 tests. The coefficient of determination or R^2-value, which was used to evaluate the closeness-of-fit, was greater than 0.90 for all models. The optimum parameter values, which are also shown in Table 1, were obtained on a size-by-size basis by determining the values corresponding to the predicted maximum separation efficiency. Separation efficiency was calculated by subtracting ash recovery to the product from combustible recovery. The maximum separation efficiency for the 28 x 100 mesh size fraction was predicted to be 40% while a value of 60% was estimated for the 100 x 325 mesh size fraction.

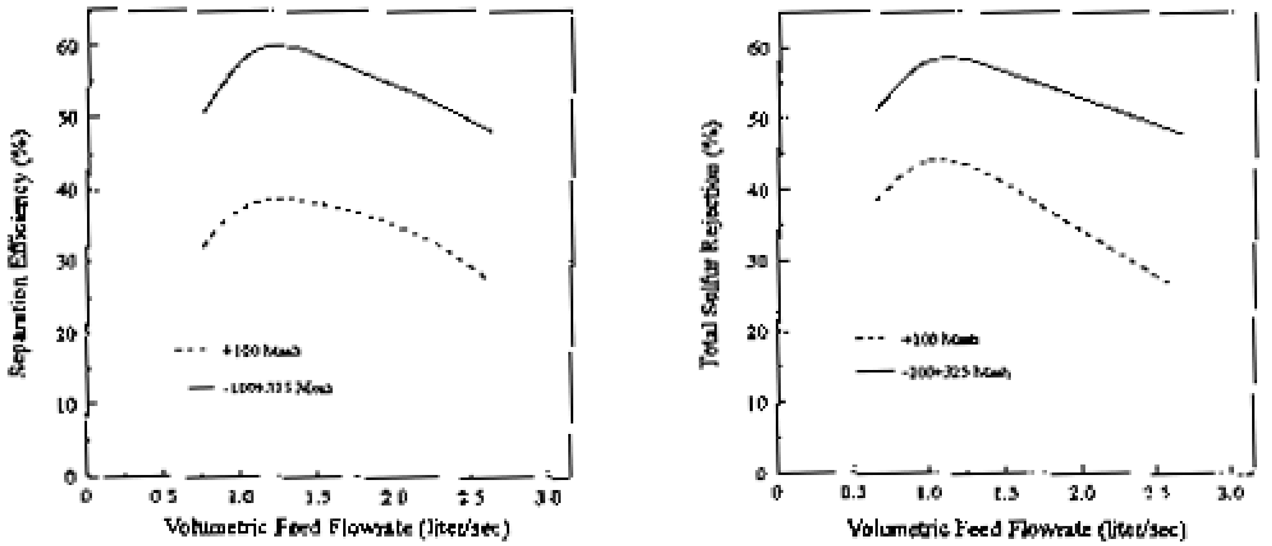
Table 1. A list of the operating parameters, the parameter value ranges studied in the Box-Behnken test program, and the optimum parameter values for the treatment of the 28 x 100 and 100 x325 mesh size fractions.

Operating Parameter	Parameter Value Range	Optimum Parameter Value (28 x 100 M)	Optimum Parameter Value (100 x 325 M)
Feed Rate (L/s)	1.26 - 2.52	1.51	1.26
Feed Solids (%)	16 30	16	16
Opening Time (sec.)	0.5 - 1.5	1.3	1.0
Bowl Speed (rpm)	473 947	568	923

Comparing the optimum values in Table 1 obtained for the two size fractions, it is apparent that the optimum feed solids content is the same for both size fractions while the optimum values of the other parameters differ. A smaller volumetric feed rate is desirable for the 100 x 325 mesh size fraction most likely due to a need for additional retention time to allow the ash-forming particles to settle to the bowl wall. The higher bowl speed was also found to be desirable for the finer fraction which is probably a result of the need for a higher *g*-force to allow the mineral particles to report to the bowl wall within the given retention time. The longer optimum opening time for the 28 x 100 mesh size fraction is likely due to the slower optimum bowl speed. The centrifugal force assists the discharge of the underflow material. Thus, to maintain a given underflow rate while decreasing bowl speed, the opening time must be increased.

Figures 2(a) and 2(b) show the significant effect that volumetric feed flow rate has on separation efficiency and total sulfur rejection, respectively, as predicted using the empirical models. For the 100 x 325 mesh size fraction, an increase in the feed flow rate from 1.26 - 2.52 L/s (20 - 40 gpm) results in a 10% decrease in separation efficiency and a nearly 8% drop in total sulfur rejection. Although combustible recovery gradually increased over the range in volumetric flow rates, ash rejection sharply decreased by nearly 20% which accounts for the reduction in separation efficiency. An increase in volumetric flow rate affects the separation performance for the following reasons: 1) reduction of the particle retention time, 2) increase in the chance of particle by-pass due to turbulence and 3) erosion of the solids bed causing beached gangue particles to report to the overflow. Further tests conducted at a flow rate of 0.63 L/s (10 gpm) found that a low volumetric flow rate also reduces separation performance. These tests were conducted separately from the experimental design and the test results integrated into the empirical expressions to obtain the low flow rate trends shown in Figure 2. From the 0.63 L/s (10 gpm) tests, low combustible recovery values were obtained, most likely due to a longer particle retention time which allowed coal particles to report to the bowl wall. Thus, an optimum volumetric flow rate exists where separation efficiency is maximum.

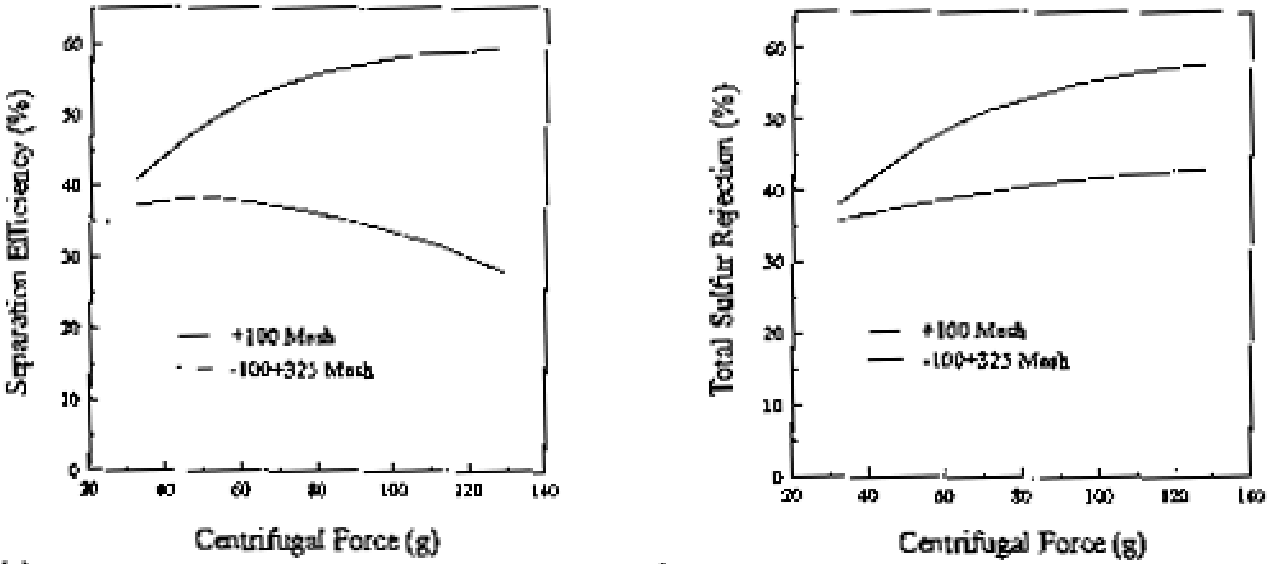
Predicted trends indicating the effect of centrifugal force on separation performance are shown in Figures 3(a) and (b). For the +100 mesh size fraction, separation efficiency gradually increases with an increase in *g*-force to a maximum of nearly 40% at 50 *g*'s. An increase in the *g*-force beyond



(a) (b)

Figure 2. Predicted trends obtained from empirical models showing the effect of volumetric feed rate on (a) separation efficiency and (b) total sulfur rejection; all other parameters maintained at their optimum values.

50 g results in a decrease in separation efficiency. This decline in separation efficiency is a result of a gradual decline in combustible recovery with little or no improvement in ash rejection. This trend results from the fact that the g-force required to allow the free gangue particles to report to the bowl wall has been surpassed and is sufficient to cause middling particles containing mostly coal to report to the inner layers of the beached solids near the bowl wall. Sulfur rejection improves throughout the range of g-force values due to the loss of organic sulfur with the combustibles reporting to tailings.



(a) (b)

Figure 3. Predicted trends obtained from empirical models showing the effect of the applied centrifugal force on (a) separation efficiency and (b) total sulfur rejection; all other parameters maintained at their optimum values.

On the other hand, separation efficiency increases sharply from 40% to 60% for the 100 x 325 mesh size fraction with an increase in centrifugal force from 40 *g* to 120 *g* as shown in Figure 3(a). The improvement in separation efficiency is due to an increase in ash rejection from 55% to 85% while combustible recovery gradually decreases by about 8% over the same range in *g*-force. Both separation efficiency and total sulfur rejection seem to be approaching maximum values of approximately 60% and 57%, respectively, at a centrifugal force of nearly 120 *g*. Based on the trend established for the +100 mesh size fraction, any increase in the centrifugal force would likely result in a decrease in separation efficiency due to particles consisting of a substantial amount of combustible material reporting to the underflow or tailings. Thus, according to this trend, an increase in *g*-force beyond 120 *g* would only be needed to achieve a desired product grade. Additional tests are being performed to confirm this trend.

Separation Performance Results

The test results shown in Table 2 summarize some of the better separation performances achieved to date. The results indicate that the Falcon concentrator has the ability to significantly reduce the ash content of the 28 x 100 and 100 x 325 mesh size fraction while achieving very high combustible recovery values of greater than 90%. These results were obtained at relatively high mass throughputs ranging from 3.9 to 9.8 tonne/hr/m^2 (0.4 - 1.0 stph/ft^2). The higher recovery values achieved by the 28 x 100 mesh size fraction indicates the ability of the Falcon unit to selectively withdraw through the underflow valves the inner portion of the solids bed while allowing the outer portion containing the coarse coal particles to by pass to the overflow. The best separation performance was achieved on the 100 x 325 mesh fraction which may be due to the relatively low ash content of the 28 x 100 mesh size fraction in the coal samples tested. The -325 mesh size fraction is not effectively de-ashed by the Falcon concentrator, however, previous tests have found that the 325 mesh by approximately 10 μm fraction is significantly cleaned. This indicates that either a desliming device or column flotation would be required to effectively reject submicron clay particles from the 28 mesh x 0 size fraction.

Table 2. Typical test results obtained on a size-by-size basis by the continuous Falcon Concentrator; volumetric feed rate = 1.26 L/s (20 gpm), feed solids content = 25% by weight, and bowl speed ≈ 1,100 rpm.

Sample	Size (mesh)	Ash (%)			Ash Rej (%)	Recovery (%)	Throughput (tonne/hr)
		Feed	Product	Tailings			
Illinois No.5 (S1)	+100	9.88	7.05	54.74	32.9	97.0	1.90
	-100+325	17.63	8.30	79.29	59.1	96.7	
	-325	53.69	53.30	80.92	2.13	99.4	
Illinois No 6	+100	4.47	3.66	11.50	26.6	90.4	1.15
	-100+325	8.48	3.97	38.79	59.2	91.3	
	-325	62.37	61.29	88.96	5.59	98.9	
Illinois No 5 (S2)	+100	7.92	6.21	52.43	24.5	98.1	0.83
	-100+325	12.80	7.33	66.29	48.1	96.4	
	-325	54.30	52.74	76.20	4.04	98.6	

As mentioned previously, initial studies investigating the use of enhanced gravity separators for fine coal cleaning were aimed at de-sulfurization of froth flotation concentrates (Luttrell et al., 1993). Table 3 shows the total sulfur reductions achieved on a flotation feed sample by the Falcon concentrator. The results show that the rejection of coal pyrite occurs before the rejection of other mineral matter in all size fractions which causes a slight decrease in the calorific value of the product. This indicates that the pyrite, which is the heaviest of the gangue minerals, forms the inner layer of the solids bed that is closest to the bowl wall. Since the combustible recovery values are relatively high, the large sulfur content in the tailing samples achieved in all size fractions indicates a substantial rejection of pyritic sulfur. The highest total sulfur rejections were achieved in the 100 x 325 mesh size fraction which may be due to the low feed sulfur content in the +100 mesh fraction and the lack of centrifugal force needed to reject ultrafine coal pyrite in the -325 mesh size fraction.

Table 3. Size-by-size sulfur reduction results achieved by the Falcon Concentrator from the treatment of the Illinois No. 5 (S2) coal sample; calorific values reported on an as-received basis.

Test Number	Total Sulfur (%)		Product BTU/lb	Recovery (%)	Total Sulfur Rejection (%)	lb SO_2 per MBTU
	Product	Tailings				
Feed (+100)	1.46		13,660			2.14
1	1.38	7.91	13,470	99.2	6.64	2.05
2	1.28	5.55	13,610	97.3	16.0	1.88
3	1.23	4.57	13,610	95.2	21.6	1.80
4	1.15	2.57	13,610	79.9	38.4	1.69
Feed (100 x 325)	1.80		12,700			2.84
1	1.53	8.76	12,525	98.7	18.2	2.44
2	1.41	5.81	13,365	96.7	28.6	2.11
3	1.29	4.65	13,430	90.4	39.2	1.92
4	1.23	3.47	13,635	80.5	49.1	1.80
Feed (-325)	1.73		5,830			5.93
1	1.44	7.86	5,855	98.5	20.5	4.92
2	1.38	6.80	6,175	97.4	25.4	4.47
3	1.32	4.99	6,220	93.5	36.0	4.25

A finding worth noting for the 100 x 325 mesh fraction in Table 3 is the decrease in the pounds of SO_2 / MBTU from 2.84 to values less than the 2.5 limit set forth by the Clean Air Act Amendment. In fact, the lbs SO_2 / MBTU value was substantially decreased in each size fraction due to relatively high total sulfur rejections and an upgrading in the calorific value resulting from substantial rejections of ash-bearing minerals. These results illustrate the ability of an enhanced gravity separator to produce compliance coal while maintaining high combustible recovery values.

Flotation Versus Enhanced Gravity Separation

Recovery-grade curves obtained by release analysis represent the best possible separation performance that can be achieved by a flotation process (Dell ,1964). Release analysis results obtained for the 28 x 100 mesh and 100 x 325 mesh size fractions of the Illinois No. 5 (2) coal sample are compared with the results obtained by the Falcon concentrator in Figures 4 and 5, respectively. In terms of ash rejection, the Falcon concentrator appears to provide a better or equal separation performance compared to that expected from a froth flotation process for both size fractions. The Falcon concentrator was also found to be more efficient at reducing the total sulfur content.

The comparisons in Figure 4 and 5 indicate that an efficient circuit for treating the 28 mesh x 0 coal may involve the use of a Falcon concentrator as the primary cleaning unit and a flotation column as a secondary cleaning unit. To reduce operating costs, a size separation at, say, 325 mesh could be conducted using a hydrocyclone whereby the cyclone underflow is a final product

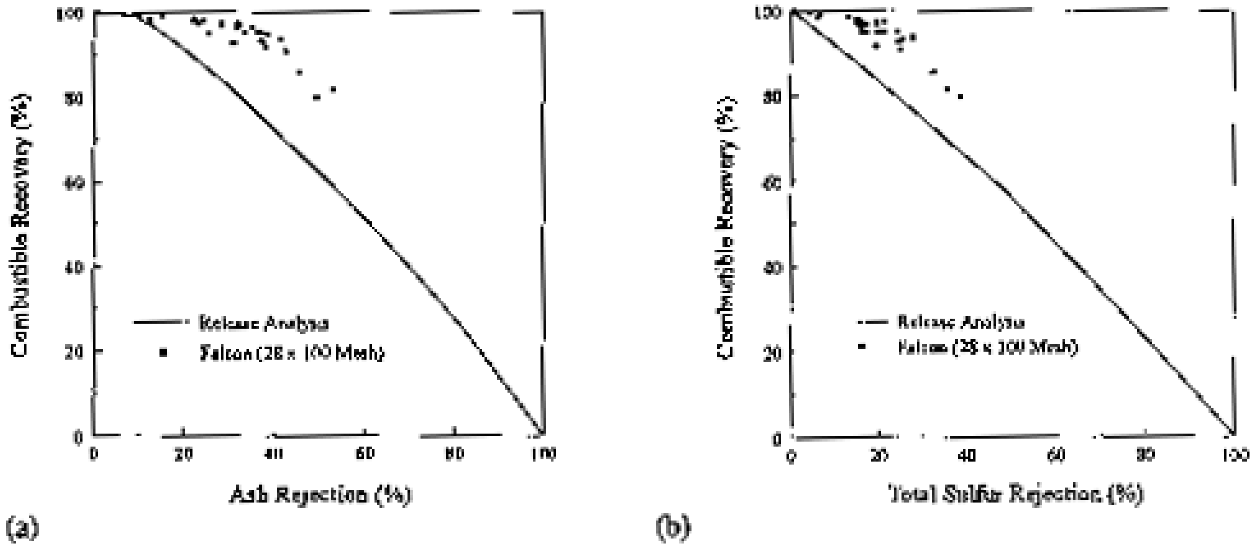


Figure 4. A comparison between the separation performances achieved by release analysis and the Falcon concentrator in terms of (a) ash rejection and (b) total sulfur rejection for the treatment of the 28 x 100 mesh size fraction.

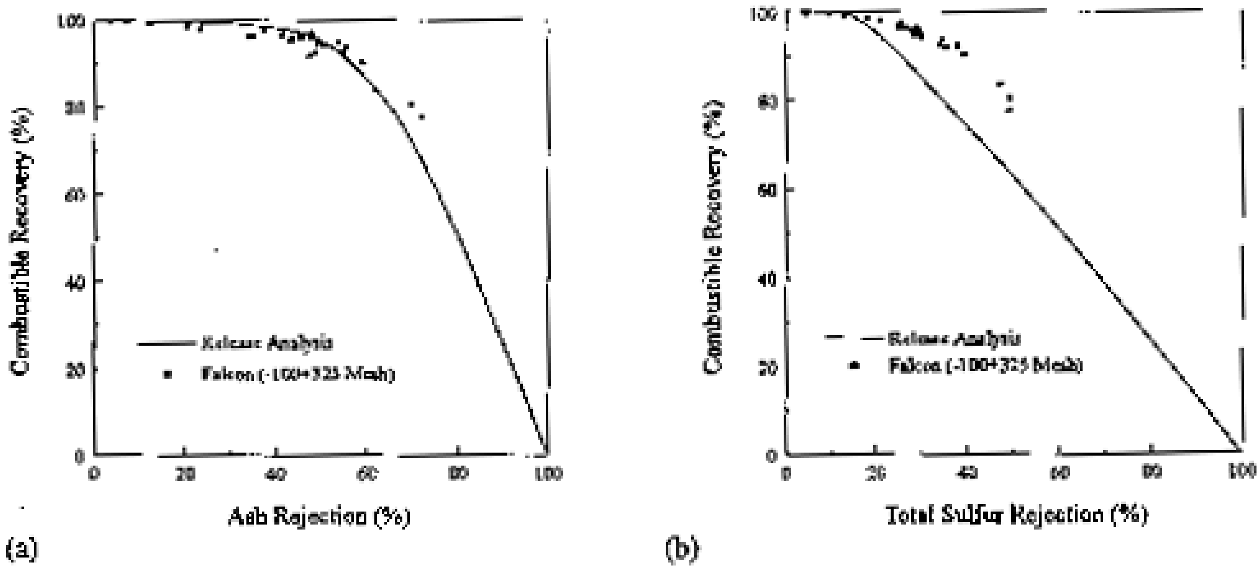


Figure 5. A comparison between the separation performances achieved by release analysis and the Falcon concentrator in terms of (a) ash rejection and (b) total sulfur rejection for the treatment of the 100 x 325 mesh size fraction.

and the overflow is the feed to a flotation column, which serves as a very effective desliming device while recovering the ultrafine coal. If the amount of combustibles in the -325 mesh size fraction is insignificant, a simple desliming unit in combination with a Falcon concentrator could be used to process the 28 mesh x 0 fine coal stream, thereby, eliminating the need for froth flotation.

CONCLUSIONS

1. The Falcon Concentrator is effective for treating coal size fractions between 28 and 325 mesh. Excellent separation performances have been achieved for Illinois No. 5 and No. 6 coal seam samples.

2. Excellent separation performances have been achieved by the 0.25 m (10-in) diameter Falcon unit at relatively high throughputs. At 1.90 tonne/hr (2.1 tph), the ash content of the 100 x 325 mesh fraction in an Illinois No. 5 coal sample was reduced from 18% to 8% with a high combustible recovery of 97%. Total sulfur rejection was 45%.

3. The production of compliance coal from a medium-sulfur coal while maintaining combustible recovery values greater than 90% is feasible using the Falcon unit.

4. The separation performance achieved on size fractions between 28 x 325 mesh was found to be better or equal to that achieved by release analysis, indicating the possibility of eliminating the need for froth flotation for treating these size fractions.

5. Feed volumetric flow rate and bowl speed were found to be critical process parameters. Increasing the volumetric flow rate above 1.26 L/s was found to decrease separation efficiency. The optimum centrifugal force for the 28 x 100 mesh and 100 x 325 mesh size fractions was 50 *g* and 120 *g*, respectively.

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