Evaluation of an enhanced gravity-based fine-coal circuit for high-sulfur coal

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Abstract

One of the main objectives of this study was to evaluate a fine-coal cleaning circuit using an enhanced gravity separator specifically for a high sulfur coal application. The evaluation not only included testing of individual unit operations used for fine-coal classification, cleaning and dewatering, but also included testing of the complete circuit simultaneously. At a scale of nearly 2 t/h, two alternative circuits were evaluated to clean a minus 0.6-mm coal stream utilizing a 150-mm-diameter classifying cyclone, a linear screen having a projected surface area of 0.5 m^2, an enhanced gravity separator having a bowl diameter of 250 mm and a screen-bowl centrifuge having a bowl diameter of 500 mm. The cleaning and dewatering components of both circuits were the same; however, one circuit used a classifying cyclone whereas the other used a linear screen as the classification device. An industrial size coal spiral was used to clean the 2- x 0.6-mm coal size fraction for each circuit to estimate the performance of a complete fine-coal circuit cleaning a minus 2-mm particle size coal stream. The "linear screen + enhanced gravity separator + screen-bowl circuit" provided superior sulfur and ash-cleaning performance to the alternative circuit that used a classifying cyclone in place of the linear screen. Based on these test data, it was estimated that the use of the recommended circuit to treat 50 t/h of minus 2-mm size coal having feed ash and sulfur contents of 33.9% and 3.28%, respectively, may produce nearly 28.3 t/h of clean coal with product ash and sulfur contents of 9.15% and 1.61%, respectively.

Key words: Coal, Fine particle processing, Enhanced gravity concentration, Linear screening, Dewatering, Screen-bowl centrifuge.

Introduction

Annual coal production in the United States is well over 1 billion tons. Nearly 45% of these coals, mostly found in eastern and midwestern states, are beneficiated in coal preparation plants due to their high ash and sulfur contents as well as other hazardous air pollutants. However, according to a recent study (Fiscor and Lyles, 2004), more than 138 of a total of 212 coal preparation plants operating in the United States directly discard their fine coal, typically the minus 150-µm particle size fraction, without any attempt to recover the fine clean coal. Hence, fine coal processing has received significant attention from the research community over the years. However, many successful fine-coal cleaning studies of the past have received limited attention from the coal preparation plant operators in spite of their encouraging results. One of the important reasons behind this indifference appears to be the isolated evaluation of fine-coal cleaning and dewatering studies. Some preparation plants having a spiral circuit to clean the 1-mm x 150-µm coal fraction use a screen-bowl centrifuge to dewater the spiral concentrate. If the plant attempts to install flotation columns to clean the finer coal fraction, the plant operators realize that a significant portion of the flotation concentrate would be lost if the existing screen-bowl centrifuge is used to dewater the fine clean coal. The dewatering option using a filtration system, which is commonly recommended for dewatering flotation concentrate, is not favored by many plant operators due to their relatively high cost and operating difficulties. In addition, many operations may have space limitations in their plants to accommodate both new fine-coal cleaning and dewatering units.

An additional problem, in relation to the high-sulfur eastern and midwestern coals is the inferior sulfur cleaning performance achieved from the froth flotation systems, which are very well known for their excellent ash cleaning performance in the finest size coal fraction. Coal pyrite particles, which are fairly well liberated at a particle size of minus 150 µm, tend to report to the clean coal product launder in a flotation cell or column due to the significant

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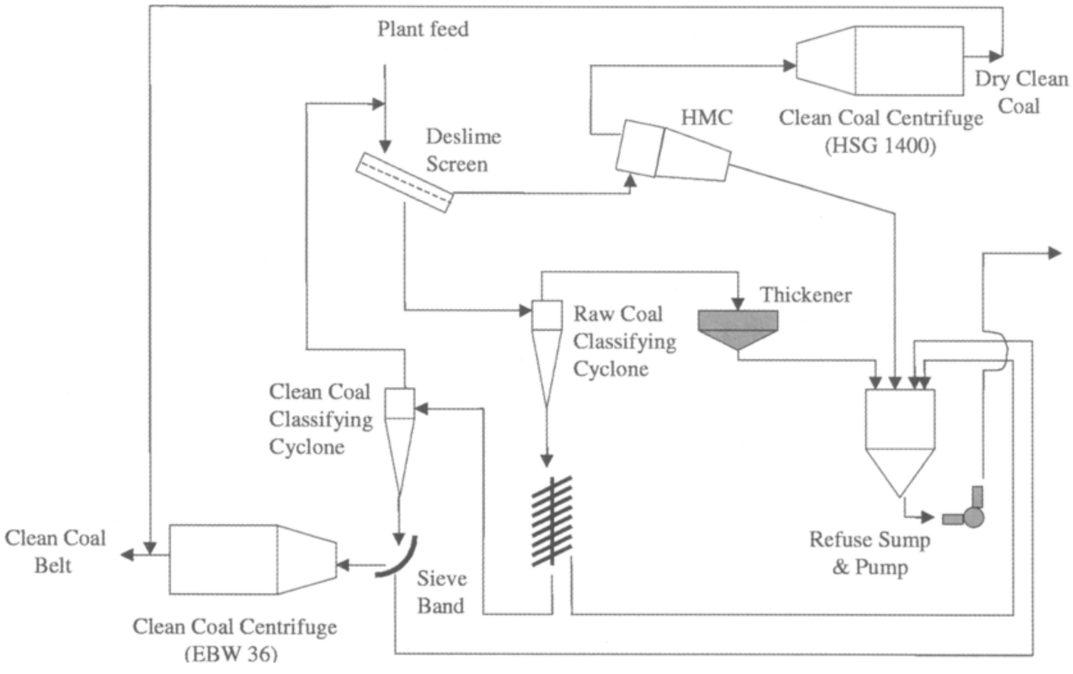


Figure 1 — A simplified flowsheet of an operating coal preparation plant in the Midwestern United States.

enhancement of their hydrophobicity by the addition of fuel oil (Olson and Aplan, 1984, 1987). Thus, froth flotation columns, which provide excellent ash cleaning, tend to achieve very minimal sulfur cleaning. In fact, in many cases, the sulfur content of flotation column product is higher than that of the flotation feed.

Several successful past studies (Honaker et al., 1995; Luttrell et al., 1995; Riley et al., 1995; Venkatraman et al., 1995; McAllister, 1998; Mohanty and Honaker, 1999) have established the effective ash and pyritic sulfur cleaning performance achieved by enhanced gravity separators, particularly in the 600- x 45-µm particle size fraction. In fact, many of these studies have reported superior ash and sulfur cleaning performance of enhanced gravity separators in comparison to flotation columns. Therefore, the present investigation utilized an enhanced gravity separator to evaluate its suitability for cleaning the 600- x 45-µm fraction. Two particle size separators, such as a classifying cyclone and a linear screen, were utilized alternatively to prepare a 600- x 45-µm particle size feed stream for the enhanced gravity separator. A screen-bowl centrifuge was utilized in combination to evaluate the actual potential of a complete fine coal circuit, including size classification, cleaning and dewatering. Based on the performance obtained from the complete circuit and from additional tests conducted using a full-scale spiral for cleaning the 2-mm x 600-µm size coal, a suitable fine-coal processing circuit has been recommended for a specific coal preparation plant treating high sulfur coal in the midwestern United States. The coal preparation plant studied during this investigation operates with a two-circuit plant, as shown in Fig. 1. The plant currently discards the entire minus 150-µm fraction of the run-of-mine (ROM) coal to a refuse pond. A successful integration of an effective fine-coal circuit may help recover a significant amount of fine clean coal and increase the plant profitability for this specific plant and many other plants operating without a fine coal circuit in the United States and elsewhere.

Experimental

Sample. As shown in the flowsheet (Fig. 1) of the preparation plant being investigated, coarse coal (plus 2 mm) is cleaned using a heavy medium cyclone (HMC) and fine coal (2 mm x 150 µm) is cleaned using coal spirals. The minus 2-mm size fraction of the ROM coal is classified using a bank of 380-mm-diameter classifying cyclones to effect a size separation at a particle size of nearly 150 µm. The feed stream to these raw coal-classifying cyclones served as the feed slurry for this pilot-scale investigation. A bulk coal slurry sample was collected over a period of several hours in an attempt to compensate for the effect of fluctuating feed characteristics. Size-by-size distributions of ash and sulfur content of this sample are listed in Table 1. Due to a total sulfur content of 3.28%, this coal may be classified as a high sulfur coal. One interesting aspect of this coal is that a majority of ash is concentrated in the minus 45-µm size fraction, whereas more sulfur is concentrated in the coarser size fraction. The feed washability data generated for the 600- x 45-µm size fraction indicate the possibility of producing a clean coal product of a low ash content of nearly 7% and a relatively low sulfur content of nearly 2% at a mass yield value of over 80% by using an effective separation process.

Experimental layout and procedure. The individual unit operations tested during this investigation included an enhanced gravity separator, a classifying cyclone, a linear screen, a spiral concentrator and a screen-bowl centrifuge. Two alternative circuit configurations, one consisting of a classifying cyclone and the other of a linear screen, were evaluated utilizing an enhanced gravity separator (having a bowl diameter of 250 mm) to clean the 600- x 45-µm size coal fraction. As shown in the schematic layouts in Figs. 2 (a) and (b), both circuits utilized a screen-bowl centrifuge (having a bowl diameter of 500 mm) to dewater the fine coal concentrate.

The bulk coal sample collected from the plant was screened at 600 µm using a gyratory screen and the resulting screen

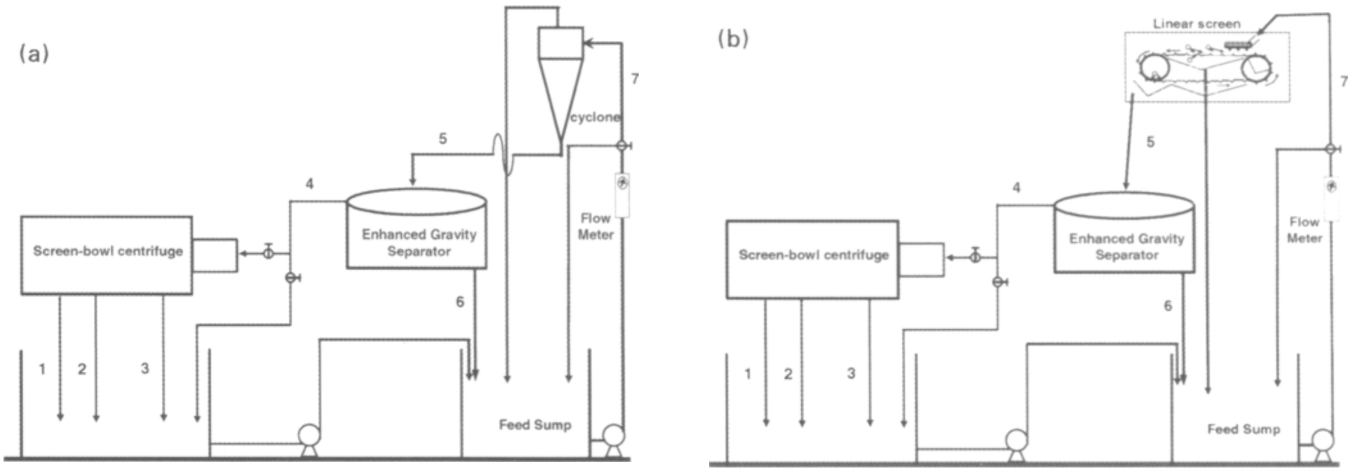


Figure 2 — The integrated circuits of fine coal classification, cleaning and dewatering evaluated during this investigation. (Numbers 1 through 7 represent the sampling points.)

underflow was used as the feed material for both circuits. The circuit feed coal slurry was further classified at 45 µm by either a 150-mm-diameter classifying cyclone or a linear screen having a footprint of 0.5 m^2 to prepare the feed material for the enhanced gravity separator having a throughput capacity of nearly 2 t/h. The overflow product from the enhanced gravity separator was dewatered by a screen-bowl centrifuge. To be able to run a series of tests at a certain time, the product streams from the screen-bowl centrifuge, the tailings stream from the enhanced gravity separator and the overflow stream from the classifying cyclone were all mixed together and recirculated to the feed tank as shown in Fig. 2 (a). For the circuit shown in Fig. 2 (b), because the linear screen utilizes a spray water system, which adds to the volumetric flow, the 45-µm size classification was conducted prior to cleaning and dewatering the screen oversize using the enhanced gravity separator and the screen-bowl centrifuge, respectively.

The slurry samples were introduced to the screen-bowl centrifuge only for a short period for collecting samples from the product streams. Due to a possible size degradation of the solid particles, the screen-bowl centrifuge was bypassed the majority of the time while recirculating the coal slurry in the rest of the circuit. To be able to determine a complete material balance around the screen-bowl centrifuge, it was desired to not recirculate the screen drain stream, which is commonly practiced in the industry to minimize clean coal loss. Samples were collected from seven specific locations shown in the flow sheets to evaluate the performance of individual units and the overall circuit.

Table 1 — Size-by-size ash and sulfur analysis and washability analysis of the fine-coal circuit feed utilized in this investigation.

Size analysis:

Size fraction, µm	Weight ash, %	Content, %	Total sulfur, %
+1,000	34.04	22.10	3.56
1,000 x 600	5.72	19.50	3.66
600 x 300	10.12	13.40	4.48
300 x 150	3.64	14.50	3.12
150 x 45	10.83	13.92	3.24
-45	35.64	61.20	2.65
Total:	100.0	33.85	3.28

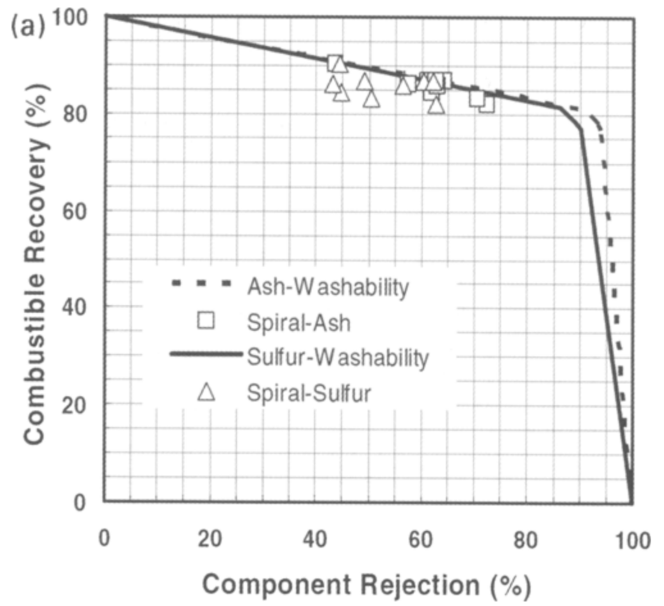
Washability analysis of 600- x 45-µm size fraction:

Specific gravity	Weight, %	Ash, %	Total sulfur, %
1.3 float	1.8	2.45	1.24
1.3 x 1.5	4.9	3.54	1.54
1.5 x 1.6	36.4	4.61	1.90
1.6 x 1.8	23.0	6.68	2.30
1.8 x 2.2	16.7	13.41	2.80
2.2 sink	17.2	48.25	7.80
Total:	100.0	13.97	3.13

Results and discussion

The preparation plant being studied utilizes only four coal spirals (two double starts) to clean the entire 2-mm x 150-µm size coal fraction and reject the minus 150-µm size coal directly to the plant thickener, as illustrated in Fig. 1. A quick calculation utilizing the size analysis data shown in Table 1 may indicate that more than 53% of the entire fine coal feed (50 t/h) being cleaned by a total of four spirals may tend to overload the spirals and cause a significant loss of clean coal. In addition, this particle size range (2 mm x 150 µm) with a maximum to minimum ratio of approximately 13:1 may be excessively wide to be efficiently treated by the spirals. Thus, it was desired to allow only the 2-mm x 600-µm stream to report to the spirals in the modified circuit arrangement and the minus 600-µm stream to the enhanced gravity separator. Prior to integrating the circuits and evaluating the two aforementioned circuit configurations, preliminary tests were conducted utilizing the main unit operations to examine their individual performance for the specific coal being used in this study.

Unit operations. Several spiral tests conducted using the 2-mm x 600-µm coal indicated satisfactory ash and sulfur rejection performance as shown in Fig. 3 (a). High combustible recovery of 90.2% was achieved while rejecting 44.3% of sulfur and 43.7% of ash present in the feed coal. The cleaning performance of the enhanced gravity separator achieved using the 600- x 45-µm size coal fraction compared satisfactorily with the ideal



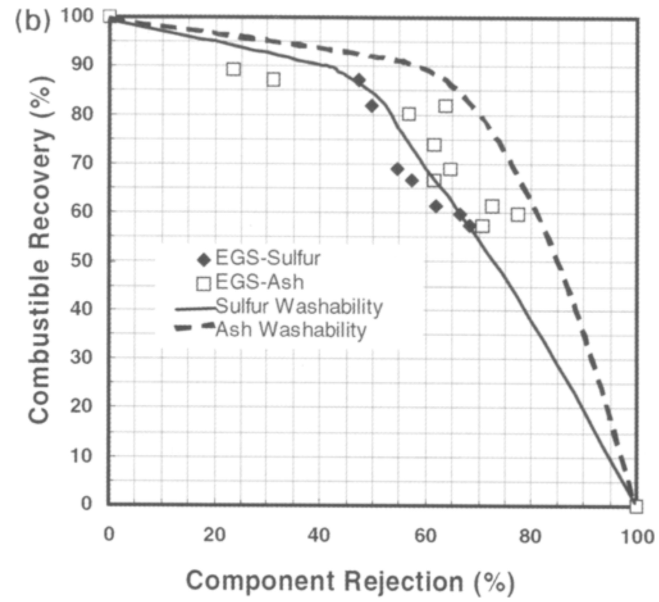


Figure 3 — Sulfur and ash rejection performance obtained (a) from the coal spiral for cleaning 2-mm x 600-µm and (b) from the enhanced gravity separator (EGS) for the 600- x 45-µm size coal.

performance revealed by the washability curves in Fig. 3 (b). The test results shown in Fig. 3 (b) were obtained by adjusting the rotational speed of the enhanced gravity separator to vary the centrifugal force in the range of 40 to 80 g and the pressure control for the underflow orifice valve in the range of 1,000 to 1,200 kPa (10 to 12 bars). The rotational speed producing a centrifugal force of 57 g and orifice pressure of 1,143 kPa (11.43 bar) provided a performance very close to the washability curve. The resulting combustible recovery, ash rejection and sulfur rejections were 81.9%, 63.8% and 46.9%, respectively. The corresponding ash reduction was from 13.5% in the enhanced gravity separator feed to 6.45% in the concentrate. This may be considered as one of the best results obtained from the enhanced gravity separator during this investigation.

A screen-bowl centrifuge was selected as the dewatering device for the proposed circuit and a detailed test program was conducted with a 500-mm-diameter screen-bowl centrifuge for dewatering minus 600-µm coal. The resulting surface moisture contents were in the range of 13.3% to 19.9%. The details of this test program will be reported in another publication.

Following the successful operations of individual units, two alterative circuit configurations, both utilizing a 250-mm-diameter enhanced gravity separator, were evaluated for cleaning the minus 600-µm coal fraction of the bulk coal slurry sample. A classifying cyclone and a linear screen were the two size classification units used alternatively in the two circuit configurations investigated. Cyclone classification, which is very commonly used in coal preparation plants, tends to force a majority of the coal pyrite particles to the cyclone underflow stream due to the density effect. Recent studies (Kroeger and Mohanty, 2004; Mohanty et al., 2005) indicate more efficient size separation performance (without any density effect) achieved by a linear screen than a classifying cyclone.

Fine coal cleaning and dewatering circuit evaluation. The two cleaning and dewatering circuits, which were evaluated separately for the minus 600-µm size coal, were the "cyclone + enhanced gravity separator + screen-bowl" (C+E+S) circuit and the "linear screen + enhanced gravity separator + screen-bowl" (L+E+S) circuit. The ash and sulfur contents of the feed slurry for both circuits were 41.8% and 3.10%, respectively. As anticipated in the circuit (Fig. 2 (a)) using the classifying cyclone, the sulfur content was enriched to 7.77% in the cyclone underflow, which served as the feed to the enhanced gravity separator. The ash content of the cyclone underflow was also relatively high at 28.0%, due to a significant misplacement of ultrafine ash-forming mineral particles. Although, the sulfur content of the enhanced gravity separator product was significantly reduced to 2.55%, the reduction in ash content to 23.4% may be considered marginal.

It is well known that the ultrafine ash-forming mineral particles tend to bypass to the overflow stream of the enhanced gravity separator, thus resulting in a relatively high ash product. The bottom particle size limit of effective ash cleaning by enhanced gravity separator is nearly 45 µm; however, effective sulfur cleaning can be achieved by enhanced gravity separator even at a much finer particle size. This phenomenon is explained by the significant density difference between pyrite mineral particles and other ash-forming mineral particles. The ash content of the enhanced gravity concentrate was lowered to 13.8% in the screen-bowl product primarily due to the elimination of ultrafine ash-forming mineral particles to the main effluent stream. However, the sulfur content was raised to 4.54% at high circuit yield level due to the preferential high centrifugal force acting upon the heavier coal pyrite particles.

As shown in Fig. 4 (a), the ash and sulfur contents of the circuit product for the C+E+S circuit were 13.8% and 4.54%, respectively, at a combined circuit yield of nearly 83%. In comparison, the product ash and sulfur contents of the L+E+S circuit were 11.8% and 2.1%, respectively, at a corresponding yield of 85.5%. The linear screen used in the latter circuit eliminated the preferential enrichment of pyritic sulfur, unlike the classifying cyclone in the former circuit. Consequently, the linear screen oversize product had a sulfur content of 3.65%, only slightly higher than the feed sulfur content of 3.10%, which was caused due to the elimination of the relatively low sulfur minus 45-µm size fraction. The ash content of nearly 19% in the linear screen oversize product was significantly

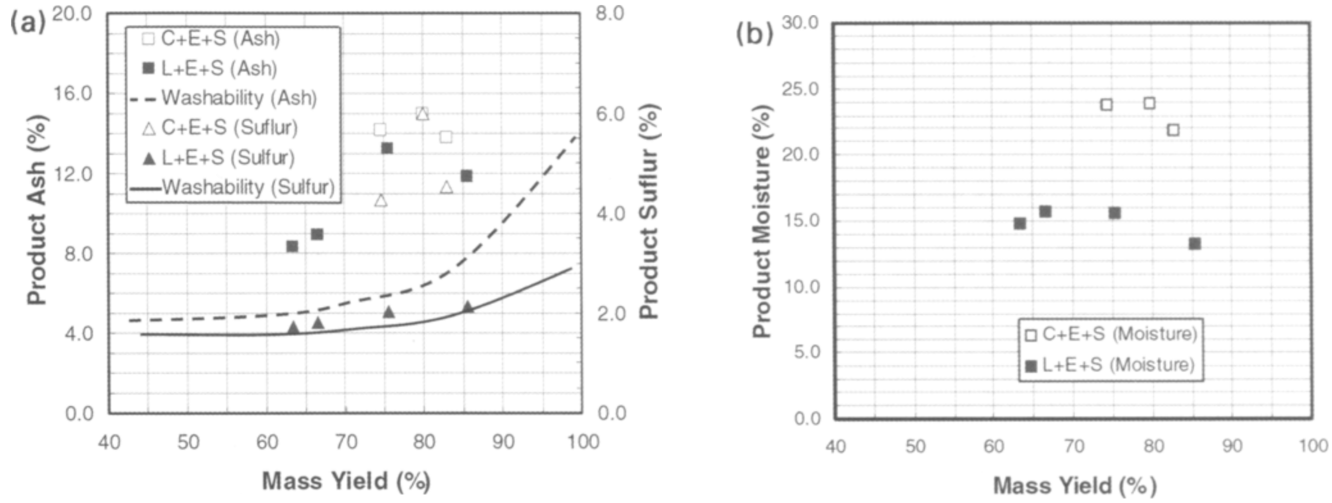


Figure 4 — (a) Ash and sulfur cleaning and (b) dewatering performance obtained from the two integrated flowsheets: C+E+S ("cyclone + enhanced gravity separator + screen-bowl centrifuge") and L+E+S ("linear screen + enhanced gravity separator + screen-bowl centrifuge").

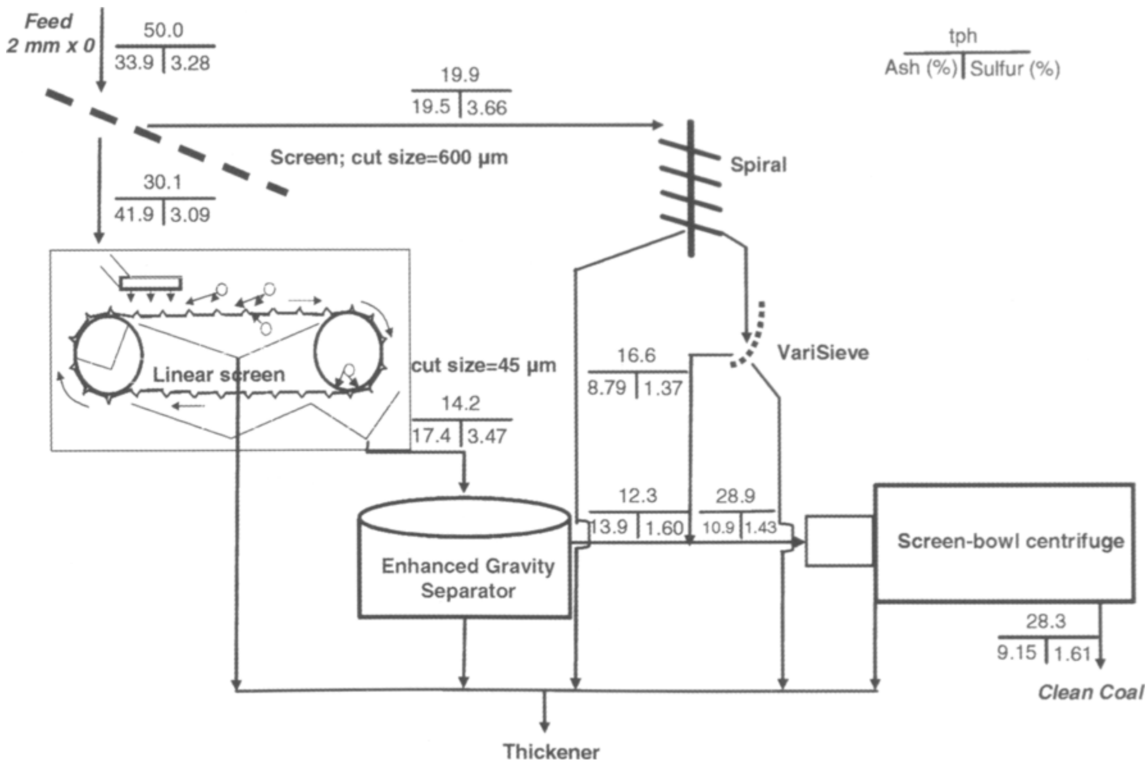


Figure 5 — The fine coal cleaning and dewatering circuit recommended for the minus 2-mm size coal fraction of the preparation plant being investigated in this study

lower than that of the cyclone underflow due to a meager 4% to 5% misplacement of high ash ultrafine particles in case of the former. Thus, the enhanced gravity separator feed in the case of the L+E+S circuit had much lower ash and sulfur contents in comparison to that of the C+E+S circuit. Lower sulfur and ash contents of the enhanced gravity separator feed stream ultimately resulted in a circuit product of lower ash and sulfur contents for the former circuit. In addition, due to lower ash content and lesser amount of minus 45-µm size particles in the screen-bowl feed stream, the moisture content of the product for the L+E+S circuit was lower than that of the C+E+S circuit, as shown in Fig. 4 (b).

Based on the aforementioned test data, a "spiral + linear screen + enhanced gravity separator + screen-bowl" circuit was recommended to effectively clean the minus 2-mm coal stream of the preparation plant studied in this investigation. Estimated mass flow rates, along with ash and sulfur assays, for the individual process streams to clean 50 t/h of fine coal are listed in Fig. 5. As shown, the flowsheet utilizes a spiral bank and an enhanced gravity separator to clean the 2-mm x 600-μm and the 600- x 45- μm coal, respectively. A linear screen is used to achieve a near perfect size separation at 45 μm. The clean coal products from the spiral and enhanced gravity separators are mixed together before being dewatered by a screen-bowl centrifuge. The coal preparation plant investigated in this study currently produces only 16 t/h of clean coal from the existing fine coal cleaning circuit. In comparison, a total of more than 28 t/h of clean coal at product ash and sulfur contents of 9.15% and 1.61%, respectively, can be produced using the recommended fine coal circuit, as indicated in Fig. 5.

Conclusions

A complete fine coal circuit, including classification, cleaning and dewatering operations, has been successfully evaluated in a pilot-scale facility to estimate its commercial potential for beneficiating high sulfur coal. An industrial size coal spiral and an enhanced gravity separator (with bowl diameter of 250 mm) were evaluated for cleaning, respectively, the 2-mm x 600-μm and the 600- x 45-μm size fraction of a high sulfur coal collected from a plant operating in the midwestern United States. A screen-bowl centrifuge (with a bowl diameter of 500 mm) was evaluated as the dewatering system along with a classifying cyclone and a linear screen as the alternative classification systems. Due to its better ash and sulfur cleaning performance, the "spiral + enhanced gravity separator + screen-bowl centrifuge" circuit including the linear screen as the classification unit has been recommended for the coal preparation plant studied. Based on the experimental data obtained from this investigation, the plant is expected to produce 28.3 t/h of fine clean coal having ash and sulfur contents of 9.15% and 1.61%, respectively, by cleaning 50 t/h of minus 2-mm size coal having ash and sulfur contents of 33.9% and 3.28%, respectively. The significant reduction in ash and sulfur content is possible due to the excellent pyrite rejection and ash rejection achieved by the enhanced gravity concentrator and the coal spiral. The recommended flowsheet may very well be suitable for any other plants treating high or medium sulfur coals.

Recommendation for future work

In recent years, coal spirals have been found to effectively treat finer size (600- x 45-μm) coal using specific operating conditions. Thus, a "spiral + spiral" circuit may be evaluated to separately clean the 2-mm x 600-μm and the 600- x 45-μm particle size coal streams as an alternative cleaning circuit configuration.

For low sulfur coal, a spiral and flotation column circuit may be worth examining to effectively clean 2-mm x 250-μm and minus 250-μm size coal.

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