Beneficiation of Fine Coal Using the Air Table

D.P. Patil* and B.K. Parekh
Center for Applied Energy Research
University of Kentucky
2540 Research Park Drive
Lexington, KY 40511

Abstract:

The increased mechanization in the underground coal mining industry has increased the volume of fine size coal and waste (refuse) in the mined coal. Processing of run-of-mine (ROM) coal is generally done using water away from mine and in some cases the coal has to be transported to a long distance to the preparation plant.. Dry processing of coal can be economical as it will not utilize water and no dewatering or drying of the product will be required.

The goal of this study was to develop a dry separation process for processing of coal finer than 6.3 mm (¼ inch). The coal sample from a mine located in Western Kentucky was used for the study. Statistical design experiments were conducted to assess the effects of operating parameters of the dry separator on product yield for a given ash content. Tests conducted with 6.3×3.35mm (and 3.35×1.4 mm size fractions showed that the air table was able to reduce the ash from 27% to 10-12% ash with a clean coal yield of 75-80%. The ash rejection was about 77-80% with a combustible recovery of around 95% indicating excellent separation efficiency. The pyritic sulfur rejection was 43%. The heat content of the 6.3×1.4 mm (1/4 ″×14 mesh) coal fraction increased from 23997 kJ/kg to 29595 kJ/kg. The pyritic sulfur was reduced by about 33% with a product yield above 80%.

Key words: fine coal, dry processing, air table, separation efficiency

*corresponding author patil@caer.uky.edu

INTRODUCTION

The thermal coal consumption in USA for the first half of 2010 was 4.8% higher than the comparable period in 2009 and it is expected that consumption growth will continue [1]. . The electric power sector (electric utilities and independent power producers) accounted for almost 93 percent of all coal consumed in the United States in 2009 [1]. However, for 2010 the coal production is projected to fall about 4% due to lower domestic demand [2]. With an ever changing economic scenario, where the demand for thermal coal varies considerably there is significant pressure on the coal industry to produce coal at lower production costs.

The quality of coal and its processing costs are definitely major factors in deciding the profitibility of a coal operation. Processing of thermal coal normally involves the reduction of inerts (mineral matter and moisture) to increase its thermal value. Generally coal is processed using water and even though wet processing of coal is quite efficient it requires an elaborate set up and in many cases is not suitable to operate near the mine site. Wet processing of coal requires large quantities of water, about 200 liters/tonne (53 gallons/tonne) [3], which is consumed as product moisture, in tailings disposal and evaporation. This is equivalent to 265 million gallons of water for a 5 Mtpa coal processing plant. The consumption of such a large quantity of water would be very difficult especially in semi-arid area. Furthermore, the effluent water from coal preparation plants can be acidic and could exacerbate the groundwater pollution problem. Another potential benefit of dry coal cleaning is the reduction in transportation costs of the run-of mine (ROM) coal which is currently being transported an average of 32 km miles to a preparation plant. Thus, deshaling of the coal near the mine site will save the transportation cost by about $3.75 per tonne/km [4].

Dry coal processing offers some advantages over wet coal processing. Even though dry coal processing may not completely replace the wet coal processing, it could be used as a complimentary step prior to wet coal processing, or in some cases, may be used to produce a saleable product.

DRY COAL CLEANING

The dry coal processing using air table was commercially introduced as early as 1916 in the USA and was quite popular for the next 50 years, reaching its peak in 1965 processing more than 25 million tonnes per year of coal. Dry coal cleaning techniques can be divided into three groups; air table, air jig and dry dense medium separator. Air table and air jigs were used to clean the coal. However, by 1985 the coal processing using these methods dramatically dropped to less than 7 million tons per year [5]. An excellent review on earlier dry cleaning processes is given by Symonds [6] and Donnelly [3].

In a pneumatic jig separator stratification is achieved through pulsating air and an oscillating deck. The average capacity for an air jig is 100 tph, for a 2.4×2.7m size unit. They are most effective when operating at high separating densities (RD >2.0), on low-ash coal feeds. Top size of feed is usually restricted to 25mm and, in general, the middlings/discard is retreated through a wet processing plant to maximize combustible recovery. The probable error (Ep) of separation is usually 0.3-0.4. At present, an air jig called the Allair jig is being successfully used for coal cleaning within and outside the United States [7].

During the year 1985, the air- tables at the Florence Mining Co, Pennsylvania were processing 1200-tph coal having top size of 19 mm [5]. In order to obtain reliable performance data, the Department of Energy conducted a series of tests with air tables in two different preparation plants [8]. The feed top size was kept at 5 cm and the feed rate varied from 90 to 150 tph. The deck oscillation was about 600 strokes/min with 6.3 mm amplitude and the pulsating air was supplied at varying rate from 60 to 268 cubic meters per minute per square meter of the deck surface. The air tables provided high separation density cuts between 1.78 and 2.67 with Ep value of 0.3. The high Ep values indicated lower efficiency, probably due to the presence of significant quantity of clays in the feed coal.

Stotts et al [9] conducted tests at the Federal mines, Elkhorn city, Kentucky to evaluate the effect of feed moisture and the performance of air table. At this plant, two Roberts and Schaefer Super Airflow, each 2.4 m wide and 2.7 m long with a rated capacities of 80 tph were used with 19×0 mm (¾″×0) feed coal. The tests results showed that Ep values were 0.24-0.26 for particle sizes above ¼″. Below 6.3 mm (¼″) in size the efficiency was so poor that an Ep could not be calculated. The tests also showed that the feed surface moisture should be maintained in the 2-3% range. The Canadian Mining Research Center conducted tests with counter-current Fluidized Bed Cascade (FBC) separator using a wide range raw coal (20×0.8 mm) with fluidizing medium comprised of limestone, hematite and/or magnetite [10]. The Ep values (0.15-0.24) showed that the separation was of a similar efficiency than those achieved by conventional Baum jig, however, better than air jig.

Even though, the dry separators provided low capital cost and maintenance, the inability to treat fine coal and lower separation efficiency contributed to their demise. Currently, China is the leader in using dry table and dry dense medium separation [11] processes. At present, in China about 130 million tonnes of coal is being processed using the dry cleaning techniques [12].

For the last five years the University of Kentucky has been involved in the studies on dry separation of coal using Air tables. The pilot-scale tests conducted at two coal mine sites in Utah showed that the dry separation of coarse coal –50×6.3 mm is feasible with the negligible loss of coal to the reject stream [13]. Even though the pilot-scale tests proved that the efficiency of the dry separator was acceptable for coarse coal (-50 × 6.3 mm), removal of –6.3 mm coal which represented 20% -25% of the raw feed coal, reduced the overall yield of the clean coal. Pilot scale data indicated that when treating 50×6.3 mm run-of-mine bituminous coal 70-90% of the grater than 2.0 relative density rock could be rejected.

The University of Kentucky also evaluated the potential of dry cleaning of coal of varying ranks using the air table [14, 15]. Results showed that regardless of the mineral matter type, rock removal into reject stream was achieved with little loss of coal. As a result, a saleable product was generated from several coal sources including lignite, sub-bituminous and bituminous coals.

The fine coal represents about 20% to 25% of the total feed coal: cleaning this coal would substantially increase the revenue of the mine and reduce the coal losses. The main objective of the present paper is to evaluate the possibility of processing the minus 6.3 mm coal on a dry Air table.

PRINCIPLE OF DRY COAL SEPARATION

Dry cleaning processes take the advantages of the differences in the specific gravity of coal and shale to effect their separation. In the case of dry dense medium processes, an air/magnetite or air/sand suspension is utilized rather than water/magnetite, which is commonly used in conventional dense medium cleaning process. The principles of operation of dry coal cleaning are identical to conventional wet processes, except that the difference in specific gravity between air and water have a significant effect upon the size ranges of particles that can be treated in a particular separator. The dry coal cleaning separators can be broadly classified into three groups: Air tables, Air jigs and Dry dense medium separators.

The Air table principle is similar to that of a wet concentrating table. Material to be separated is fed onto the narrow side of a flat deck covered with perforated screen which is sloped in two directions and vibrated with a straight line reciprocating motion. Low pressure air, blown upward through the deck, fluidizes and stratifies the material according to difference in the terminal velocity of the particles. The heavier particles settle to the bottom; where further movement down the table was hindered by riffles, travel in the direction of the deck's vibration. The lighter particles lifted by the fluidizing air and assisted by gravity travel down the slope towards discharge end and separate into middling and clean coal at the end by splitter plates. Affected by both the vibration and airflow, the material bed thins as the deck broadens toward the discharge end. Here, the material is arrayed from heaviest to lightest in as a layer on the deck that can be precisely and easily divided in to multiple fractions. Recent air table models accept a top size of 3 inch (75 mm) with a higher capacity of more than 300 tph.

Theory

For the sake of completeness, a brief account of theory of dry separation is given. Detail theory is given elsewhere [5]. Because of many interactions between the suspending medium and the particles of varying size, shape and specific gravity occur simultaneously, till now no complete satisfactory theoretical models have been developed. Due to the complexities involved in developing theoretical models, numerical methods are being developed to understand the settling of the particles [13]. However, to explain the basics of dry separation the following simple model is sufficient.

Rittenger in 1867 developed the theory of equal settling of particles which gives an insight to the settling of particles having various diameters and specific gravities, which would each have equal terminal velocities falling through a medium of specific gravity ρ_m. The settling ratio is equal to limiting ratio of diameters of particles which may be separated by free settling.

$$Settling\ \ ratio = \frac{d_L}{d_H} = \frac{\rho_H - \rho_m}{\rho_L - \rho_m}$$

Where d_L = diameter of particles of specific gravity ρ_L

d_H = diameter of particles of specific gravity ρ_H and $\rho_L < \rho_H$

Therefore, particles of coal (sp.gr. 1.40) and shale (sp.gr. 2.60) settling in air (sp. gr ≈ 0), have the settling ratio equal to 1.86 or about 2. In other words spherical particles of coal and shale may be separated while falling in air if they are within a 2:1 ratio. However, if the air is replaced by water, the settling ratio will be 4.0. Theoretically, thus a simple water medium process separation is possible within a 4:1 particle size ratio, as compared to a 2:1 particle size ratio for an air medium separator.

Instead of using fluid medium density, the effective bed density could be used which simulates the buoyancy effect of the interacting bed of particles, enabling the calculation of hindered settling ratio. Assuming a coal and shale mixture containing 25% shale and 75% coal at 40% solids by volume, the hindered settling ratios are 2.8 and 21.0 in air and water media respectively. Also, in both jigs and tables, the differential acceleration of particles is provided by the controlled oscillating motion, which is well known to assist stratification of particles.

Figure 1 shows the theoretical settling ratio of particles for air as a medium. It shows that a settling ratio of 40:1 exist after 0.005 seconds free fall, decreasing to 5:1 after 0.02 seconds, and to 2:1 at more practicable time intervals. For water as a medium a settling ratio of 40:1 existed after as much as 0.12 seconds.

Even though, these theoretical analyses give only limited explanations, however, they do confirm that a restricted size range is logical for air separators and high frequency oscillations would be necessary for efficient separation of a wide size range of particles.

EXPERIMENTAL

An air table, supplied by the Bratney Companies, Des Moines, Iowa, was used for the present study. The principle of operation of this air table is similar to the one described in the previous section. Figure 2 shows the moving pattern of different particles on the air table. The heavier particles such as shale, quartz and pyrite move towards the ports numbered A, and B, whereas middling particles, which is a mixture of unliberated coal and shale, moves towards the ports C and D. The coal particles being lighter move towards the ports E, F and G. It was observed that closing the port D provides better separation probably due to increased residence time on the table. For the present study the samples were collected from ports A, B, C, E, F and G. Majority of coal particles were reported to ports F and G, while port A received major fraction of rejects.

RESULTS AND DISCUSSIONS

A Run-of-mine coal sample was collected from a coal mine located in Western Kentucky. The sample was crushed to -6.3 mm and was further screened to obtain -6.3×3.35 mm, -3.35×1.4 mm and -1.4 mm size fractions. These size fractions were selected based on the earlier discussions on settling ratios required for dry coal separation. The -1.4 mm sample was not used in the present study mainly due to its handleability problems. The analyses of each size fraction are given in Table 1. The 6.30×3.35 mm of coal sample contains slightly higher ash (29%) compared to 3.35×1.40 mm and -1.40 mm fractions. The data shows that as the particle size becomes smaller, the ash content decreases from 29% to 21%. The pyritic sulfur, sulfate and organic sulfur are fairly uniform in all size fractions.

Sink-float tests were carried out on 6.3×3.35 mm and 3.35×1.4 mm size fractions of the coal sample using lithium meta-tungstate solution to determine the separation as a function of density. Figure 3 summarizes the float-sink data of cumulative product ash with cumulative product yield. The Figure 2 indicates that both size fractions have similar cleaning characteristics. It can be seen that at about 10% product ash, the ideal clean coal product yield will be around 85%.

Air Table Separation Study

An air table, supplied by the Bratney Companies, Des Moines, Iowa, was used for the present study. Figure 2 shows the moving pattern of different particles on the air table. The heavier particles such as shale, quartz and pyrite move towards the ports numbered A, and B, whereas middling particles, which is a mixture of unliberated coal and shale, moves towards the ports C and D. The coal particles being lighter move towards the ports E, F and G. It was observed that closing the port D provided better separation probably due to increased residence time on the table. For the present study samples were collected from ports A, B, C, E, F and G.

Evaluation of air table parameters and optimization

Based on the earlier experiments conducted with coarse coal (50×6.3mm) [13], three air table variables, namely, table frequency, longitudinal and transverse angles were examined in the present study. A statistically designed set of experiments using the Box-Benkhen design were conducted to determine the most significant operating variables. The variables and their respective value range used for the statistical design were:

Table frequency (30 -50 Hz) (A)
Longitudinal angle (0.5 -2.0 degree) (B)
Transverse angle (5.0 -8.0 degree) (C)

The fluidization air blower frequency was kept constant (45 Hz) throughout the study. The Box-Benkhen design and responses obtained are listed in Table 2 and 3 for 6.3×3.35 mm and 3.35×1.4 mm size fractions, respectively. It was noted that the product ash contents within the test matrix for both size fractions only varied slightly between 10-13%. Hence, the product yields were calculated for a constant product ash using cumulative product and ash values of each sample. Figure 4 shows a typical product recovery-grade curve for each experiment. It can be seen from the figure that the product ash fairly remains constant (7-8%) with a cumulative product yield of 70%, indicating efficient separtion of coal and rock particles. The Tables 2 and 3 show the product yields for 12% and 11% ash respectively.

Empirical models describing the product yield as a function of the operating parameter values can be written respectively for 6.3×3.35 mm (Eq. 1) and 3.35×1.4 mm (Eq. 2) coal size fractions as,

Yield (%) = 2.62 + 0.76×Table Frequency + 4.5× Longitudinal Inclination + 24.58 × Transverse Inclination + 0.2 × Table Frequency × Transverse Inclination - 0.033×Table Frequency - 2.92 × Transverse Inclination^2 [1]

Yield (%) = 150.8 - 0.75×Table Frequency + 2.83×Longitudinal Inclination - 8.41 × Transverse Inclination [2]

The coefficients in Eqs. [1] and [2] and their significance are provided in Tables 4 and 5. The associated p-values ("Prob > |F|") are interpreted as the probability of realizing a coefficient as large as that can be observed, when the true coefficient equals zero. In other words, small values of p (less than 0.05) indicate significant coefficients in the model.

Table 4 shows that all three parameters are important for the 6.3×3.35 mm coal, where as for 3.35×1.4 mm fraction (Table 5), only the table frequency and the transverse angles are important as indicated by the ‘F’ values. It was surprising to note that the longitudinal angle was not an important parameter for the product yield. It was expected that the product yield will increase with increase in longitudinal angle due to the increased slope towards product discharge end. During the testing, it was observed that the coal particles are easily lifted by upward air flow and move rather quite freely towards product end. Hence, the longitudinal angle might not have had the expected effect on the product yield. The effects of each parameter on the product yield are pictorially depicted in the perturbation graphs (Figures. 5 and 6). The quadratic nature of the curves A and C shows that table frequency and transverse inclination are important parameters (Figure 5). This conclusion is supported by the very low value of 'F' values. An increase in transverse inclination increases the product yield. This could be attributed to the higher volumetric flow rate of solids to the product end, which removed higher fraction of stratified material from the table thus, increasing the cut point. The higher table frequency in both cases decreases the product yield, thus indicating larger movement of material towards tailings end. During the testing with coal fractions, it was observed that the entire particle bed moved quickly towards tailings discharge end. This behavior may be due to the fact that at higher table frequency the particles move on the table even before they had any chance to get stratified.

The effects of the longitudinal inclination and the table frequency are pictorially shown in Figures 7 and 8 for both size fractions. These figures show that an increase in table frequency decreases the product yield. In case of 6.3×3.35 mm size fraction longitudinal angle increases the product yield; however, for 3.35x1.4 mm size fraction it does not have any affect. The interactive effect of transverse inclination and table frequency is shown in Figure 9 for the 6.3×3.35 mm size fraction. At a transverse inclination of 5° and table frequency of 30 Hz the yield is about 71%. However, at the same transverse inclination of 5°, an increase in table frequency from 30 Hz to 50 Hz decreases the product yield from 71 % to about 60%. Conversely, at a transverse inclination of 8°, increasing the table frequency reduced the yield from 59% to 50%. This decrease in product yield could be mainly due to the transportation of material towards tailings end without stratification.

Equations 1 and 2 were used to optimize the yield or achieving maximum separation efficiency. A steepest ascent/descent optimization routine was utilized to maximize/minimize the desirable merit function for optimization of response. The goal was to maximize the product yield by changing the table operating parameters. By changing the criteria used to achieve the goal, it was possible to obtain conditions for factors under which the product yield could be maximized. These conditions are summarized in Table 6, which shows that at lower table frequency (A), the model suggest using lower longitudinal and transverse angles, whereas at a slightly higher table frequency (38-50) higher longitudinal angle is necessary achieve a similar product yield. As explained earlier, increasing the table frequency tends to push the particles to tailings end thus reducing the particle residence time on the table, which could be compensated by increasing longitudinal and transverse angles.

Figure 10 shows a picture of the 3.35×1.4 mm mesh coal being processed on the air table. The picture shows that the separation of rock from the coal is efficient without loss of much coal to rejects. Table 7 shows the optimized air table data for obtaining a product ash of 12% at a yield of 75-80%. The ash rejection was about 77-80% with a combustible recovery of about 95% indicating excellent separation efficiency.

Experiments with 6.3×1.4 mm coal

Preliminary experiments were carried out by combining the 6.3×3.35 mm and 3.35×1.4 mm coal fractions to investigate the effect of feeding wider particle size distribution to the air table.The parameters were selected based on the studies carried out on individual coal size fractions. The parameters and the results obtained are given in Table 8. It can be seen from the table that the product ash almost remained constant at different operating conditions similar to the observations made with closely sized fractions. However, the product yield varies considerably between the operating conditions. Table 8 shows that the product yields (run 2 and 3) were higher (83-85%) than the yields obtained with closely sized fractions (75-80%). This probably could be due the removal of fines present in the sample during experimentation with individual size fractions providing better separation with the mixed sample. The heat content of feed coal sample was upgraded from 23,997 kJ/kg to 29,595 kJ/kg with about 30% rejection in pyritic sulfur and 62% ash rejection. It can be concluded that the 6.3×1.4 mm coal fraction may be successfully be processed using the air table.

CONCLUSIONS

Based on the results of the study it can be concluded that,

- For the coal selected for the study the air table was able to reduce ash from 27% to about 10% at a yield of 80%, which was similar to the results obtained in the washability studies.
- For the 6.3×3.35mm size coal fraction, all three parameters; table frequency, longitudinal and transverse angles were found to be important. Whereas, for 3.35×1.4 mm size fractions only table frequency and transverse angles were found to be important.
- The table frequency had a significant effect on the product yield. At higher frequencies most of the particles moved towards tailings discharge end without undergoing much separation. Lower frequencies provide better clean coal yield.

- For the closely sized fractions the ash rejection was about 77-80% with a combustible recovery of about 95%, indicating excellent separation efficiency. The pyritic sulfur reduced from 2.65% to about 1.5% indicating 43.3% reduction.
- Using the dry separation technique the heat content of the 6.3×1.4 mm coal fraction increased from 23,997 kJ/kg to 29595 kJ/kg (10236 Btu/lb to 12623 Btu/lb). The pyritic sulfur content reduction was about 33%.
- The air table study showed that dry separation of a wider size 6.3×1.4 mm size coal fraction is feasible .

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