A Laboratory Scale Investigation Of Dry Coal Beneficiation In An Air Fluidized Bed: Effects Of Particle Size, Shape And Density

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***Abstract*—** Coal is a fossil fuel that forms under the earth by natural processes. The Potential markets for coal include power generation, export, domestic, metallurgical, liquefaction and cement processing industries. In Kenya, coal is found in arid areas of Kitui County but mining and processing operations are yet to begin. One factor that could impede the development of a coal processing plant in Kitui, besides environmental related challenges (such as the carbon footprint) is the scarcity of water. A need thus exists to research on dry coal beneficiation methods to avoid reliance on the conventional wet processing methods. Dry coal beneficiation with an air dense-medium fluidized bed is one of the dry coal processing methods that have proved to be efficient. In this study a (40 x 40x 60) cm dry batch air fluidized bed coal separator with a relatively uniform and stable average magnetite-silica bed density of 1.64 g/cm^3 was employed for the detailed separations test using particles of different densities, shapes and sizes. Coal particles size ranges varied from (+9.5 -53mm) while the different particle shapes tested were blockish (+16-22mm), flat (+16 -22mm) and sharp pointed prism particles (+16 –22mm). The (+37 -53mm) and (+22 -31.5mm) particles separated faster and more efficiently than the (+16-22mm) and (+9.5 -16mm) particles. Further, the separation efficiency of the particles improved at longer bed depths with relatively uniform and stable bed densities. Therefore, prescreening of the coal particles into relatively narrow ranges would be important in the optimization of dry coal beneficiation using an air fluidized bed since different particle size ranges and shapes have different optimum conditions required for efficient separation.

***Keywords*—** *Fluidized bed, Dry coal beneficiation.*

I. Introduction

Research on dry beneficiation technology with fluidization in coal preparation started more than 50 years ago [1]. Different research groups in the United States, Netherlands, China, Canada and South Africa have contributed in various ways in the development of this technology. In 2003, researchers from Delft University of Technology, Netherlands constructed a pilot sized separator and used it to carry out some detailed experiments. The researchers from Delft University of Technology concluded that the performance of the fluidized bed was quite comparable to the conventional wet jigging process with average separation inefficiency, Ep of 0.1 being obtained. Dry beneficiation of coal with an air dense-medium fluidized bed is an efficient coal separation method characterized by an average industrial Ep of 0.05. It utilizes an air-solid suspension as beneficiating medium whose density can be maintained with consistency, similar in principle to the wet dense medium beneficiation using liquid-solid suspension as separating medium.

The air-dense medium fluidized bed used in dry coal beneficiation is not only pseudo fluid in nature, but also has a stable and uniform density. The heavy particles in feedstock whose density is higher than the density of the fluidized bed will sink, whereas the lighter particles will float, thus stratifying the feed materials according to their density [1].This technique introduces a new method of coal beneficiation for the regions where water resources are in short supply and for the coals which tend to slime with wet separation processes.

In South Africa, some researchers from the University of Kwazulu Natal, Minerals Processing Research group have done some considerable work aimed at developing this novel dry coal processing system. Initially semi-batch tests were conducted using density tracers followed by batch separation of discard coal which varied in size between 1.5 –3.5cm. A novel collecting mechanism was also constructed to aid in the removal of the materials from the bed. At optimum conditions, separation inefficiency (Ep) of 0.0458 was obtained when separating the high ash Waterberg coal at an approximate average separation density of about 1996 kg/m3. Continuous test work at a flow rate of 18 kg/hr yielded an Ep of 0.0462 at the same density. The experimental data demonstrated that dry separation can be as efficient as the corresponding wet processes [2].

In order to obtain an efficient dry separation condition in an air-dense medium fluidized bed, stable dispersion fluidization and micro bubbles must be achieved. The main requirements are that the bed density is well distributed in the three-dimensional space, not changing with time, and that the bed medium is of low viscosity and high fluidity [3]. When a homogeneous and stable level of bed density with air-dense medium fluidized bed is established, a dispersion fluidized bed with dense-phase, high density, and micro bubbles is formed. The pure buoyancy of beneficiation materials plays a major role in maintaining the fluidized bed density, and the

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displaced distribution effect should be restrained. The displaced distribution effects include viscosity-displaced distribution effect and movement-displaced distribution effect. The former mostly affects fine materials occurring when the fluidized bed has high viscosity. It reduces with increased air flow velocity. The value of the latter will be large when air flow rate is much lower or higher than the optimum required to maintain a stable fluidized bed. If medium particle size distribution and air flow are well controlled, both displaced distribution effects will be restrained effectively [3].

Mixtures of magnetite powder and fine coal can be used as dense medium in a fluidized bed to produce a stable and uniform beneficiation density ranging from 1.3 to 2.2 g/cm^3. Therefore, this technology can meet the needs of beneficiating different coals for various products. It can either be used to remove gangues at high density or to produce clean coal at low density. By the Archimedes Law, light and heavy particles separate from each other by the bed density with the light particles floating and the heavy particles sinking. Although considerable literature survey suggests that applications of the fluidized bed dry coal separator can been done successfully on an industrial scale as demonstrated in other countries such as China and Germany, there is still need to understand how various factors interact and develop models that would lead to better control and optimization. Hence as part of this study, the effect of particle size, shape and density on the performance of an air fluidized bed in dry coal beneficiation is investigated. The broader aims are: (a)To develop a sound understanding of the key process parameters which govern the kinetics of coal and shale separation in an air fluidized bed focusing on the effect of the particle size, shape and density on the performance of the fluidized separator. This understanding will be applied in the analysis and possibly further development of the continuous process. (b) To integrate coal comminution and preparation with end uses so as to ensure adequate liberation and to optimize the use of the air fluidized bed through the manipulation of the particle size, shape and density. This is in the hope that coal comminution can be optimally controlled in relation to the mechanism of fracture, resulting in the production of particles of optimal shape and size.

II. FUNDAMENTAL THEORY OF AIR-FLUIDIZED BEDS

An air fluidized bed is formed by passing air upwards through a bed of particles supported on a distributor. Although, it is now known that even above the minimum fluidization velocity the particles are touching each other most of the time, with the exception of cohesive solids, the inter-particle friction is so small that the air / solid assembly behaves like a liquid having a density equal to the bulk density of the powder. Pressure increases linearly with distance below the surface, denser objects sink, lighter ones float, and wave motion is observed. The behavior of particulate solids in a fluidized bed depends largely on a combination of their mean size and density [4] and it has become increasingly common to discuss fluidized systems in relation to the so–called Geldart fluidization diagram. This is used to identify the package of fluidization characteristics associated with fluidization of any particular powder at ambient conditions.

In dry dense medium separation, the size of separated materials is much larger than that of the fluidized particles, which can be treated as a continuum. The drag force on a spherical object moving in a fluidized bed can be expressed as follows [5]:

$$F_d = C_d \pi \left(d_o / 2 \right)^2 \left(\rho_{bed} u_r^2 / 2 \right) \tag{1}$$

Where F_d is the drag force, C_D is the drag coefficient, d_o is the diameter of object, v_r is the relative velocity of an object and the fluidized particles and ρ_{bed} is the bed density.

A spherical particle immersed in a fluidized bed is subjected to the following forces: gravity, effective buoyancy (due to hydrostatic pressure distribution) and drag forces. The drag forces are contributed by the relative motion of the particle and gas, and of the spherical particle and fluidized particles. Drag forces contributed by the relative motion of the particle and gas can be neglected. The effective buoyancy force on the spherical particle can be calculated by Archimedes' principle, as it is immersed in real fluid with the density equal to the bulk density of fluidized bed. The motion equation of a particle falling through the fluidized bed can be written as:

$$\frac{\pi}{6} d_o^3 \rho_o g - \frac{\pi}{6} d_o^3 \rho_{bed} g - C_d \pi \left(d_o / 2 \right)^2 \left(\rho_{bed} u_r^2 / 2 \right) = \frac{\pi}{6} d_o^3 \rho_o \frac{du_o}{dt} \tag{2}$$

Where ρ_0 is the density of spherical particle and u_0 is the falling velocity of spherical particle. When the falling velocity reaches the terminal settling velocity u_t, $du_o/dt = 0$. As u_t is much larger than the flow rate of fluidized particles under close to minimum fluidization conditions, $u_r \cong u_t$.

The bed viscosity of an air fluidized bed decreases as gas flow rate increases. The rate of decrease of viscosity is greatest near incipient fluidization, there after the rate of decrease lessens. Fluidized bed viscosity is related to bed voidage by eq.3 where all the terms have the same meanings as defined before.

$$\mu_a = \mu \frac{1 + 0.5(1-\varepsilon)}{\varepsilon^4} \left(\frac{1-\varepsilon}{\varepsilon} \right)^9 \tag{3}$$

Although little quantitative work has been carried out on the characterization of the particle shape, it is known that it influences such properties as flowability of powders, packing and interaction with fluids. Given the fundamental importance of particle shape in fluid dynamics, it is therefore

necessary to be able to measure and define shape quantitatively. Terrance [7] stated that there are two points of view that have been raised regarding the assessment of particle shape. One is that the actual shape is unimportant and all that is required is a number for comparison purposes. The other is that it should be possible to regenerate the original particle shape from the measurement data [7].The numerical relations between the different sizes of a particle depend on the particle shape, and the dimensionless combinations of the sizes are called shape factors. The relations between measured sizes and particle volume or surface are called shape coefficients.

The pressure drop across a fixed bed height H containing a single size of isotropic solids is given by the Ergun equation:

$$\frac{\Delta P}{H} = 150\frac{(1-\varepsilon)(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu U}{d_p^2} + 1.75\frac{1-\varepsilon}{\varepsilon^3}\frac{\rho_f U^2}{d_p} \qquad (4)$$

The minimum fluidizing velocity is a very important parameter in both the design and operation of fluidization technologies. The basis of the theory for prediction of minimum fluidization velocity is that the pressure drop across the bed must be equal to the effective weight per unit area of the particles at the point of incipient fluidization. Minimum fluidization velocity, Umf is the velocity of the fluid at which the above condition is satisfied. The minimum fluidization velocity can be estimated by either using equation

Segregation in gas-solid fluidized beds has been found to be stronger for the heterogeneous systems than the homogeneous ones. Density difference of the medium particles is one of the major factors affecting segregation. Some of the system variables or parameters that affect segregation in gas – solid fluidized beds include the initial static bed height, composition of the mixture, superficial velocity of the of the fluidizing medium, the flotsam and jetsam concentration, particle characterization of the material to be separated (i.e. particle density, size and shape), bubble diameter, bubble rise velocity, bed voidage fraction, fraction of bed in bubbles, minimum fluidization velocity. Knowledge of the minimum fluidization velocity and the mechanism of the segregation are crucial to the behavior of the fluidized bed and need to be properly understood as they significantly affect the overall performance of the fluidizing bed. Much work has been devoted to investigating the segregation of particles by size and to a less extent by density and shape [8].

III. EXPERIMENTAL SETUP AND METHODS

A 40 x 40 x 60 cm rectangular three-dimensional batch fluidized bed was designed and constructed from perspex reinforced using a steel framework at the edges In order to ensure a uniform air distribution throughout the bed, a uniform canvas distributor sandwiched between two pieces of wire mesh was used. The experimental setup used for the laboratory tests is shown in the process flow diagram (Figure 1). A pressure regulator was used to ensure a constant air supply of 320 kPa throughout the tests. As for the pressure measurements inside the bed, a pressure probe made from a polythene tube with graduations ranging from 0mm to 500mm was used to measure the pressure drop across the bed.

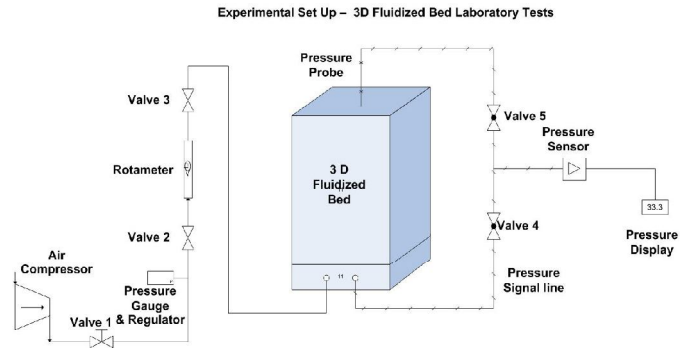

Fig1. Experimental setup for air fluidized bed laboratory tests

Coal particles of different shapes and densities ranging from 1.30_2.70were picked from the following four size ranges: +9.5–16mm; +16–22mm; +22–31.5mm; +37–53mm. Particle shape is a difficult parameter to define quantitatively. Hence, particles that resembled the blockish (Blk), flat (FB), and sharp-pointed prism qualitative shape descriptions were visually selected. Laboratory float and sink tests using mixtures of carbon tetrachloride and benzene were initially used to determine the various particle density ranges, while the specific density of each particle was determined using a water displacement method based on the Archimedes' principle. At least six particles were selected from each of the particle density intervals, size ranges, and shapes outlined above. A fixed bed height of 32cm and an average bed density of 1.64 were used for the detailed separation tests using coal particles within the particle size range of +9.5–53mm and density range 1.30–2.60. The bed was allowed to reach a stable fluidization state before any feed sample of the material to be separated was introduced from the top of the Bed. After running for different time intervals the air was stopped and all the particles recovered above the 20 cm bed height were classified as floats whilst those recovered below the 20 cm mark were regarded as sinks. In order to improve the precision and accuracy of the results, the above tests were repeated at least three times. The collected data were then used to plot the partition curves for the different particle size ranges and shapes. The partition coefficient was defined as the percentage of feed material of a certain nominal specific gravity that reported to the sinks [9].

IV. RESULTS AND DISCUSSION

A. Separation Tests using Coal Particles

Dynamic and steady state partition curves were plotted for the different particle size ranges and shapes. The partition curves were analyzed both graphically and using the Klima and Luckie model, which is one of the widely used partition

functions [10]. The Ep and ρ_{50} values obtained using the graphical method compared very well with those obtained using the Klima and Luckie model. The Klima and Luckie model is given as

$$Y_i = \frac{1}{1 + \exp\left[\frac{1.099(\rho_{50} - \rho)}{Ep}\right]} \quad (5)$$

Where Yi is the partition coefficient, ρ_{50} is the cut density, ρ is the particle density, Ep is the separation inefficiency and 1.099 is an empirical constant. The partition curves were obtained by plotting the average partition coefficient (%Sinks) for each density range against the respective nominal average relative density. Figure 2 illustrates the partition curves for the +37–53mmparticles obtained after the different separation times of 15 s, 30 s, 60 s, and 600 s. The separation times of 15 s, 30 s, and 60 s were chosen based on the results from the preliminary tests that indicated that the rise and settling velocities of the particles in the fluidized bed were relatively high and within 60 seconds the separation process would be complete. The separation time of 600 seconds was only used as a guide on the performance of the bed under equilibrium conditions.

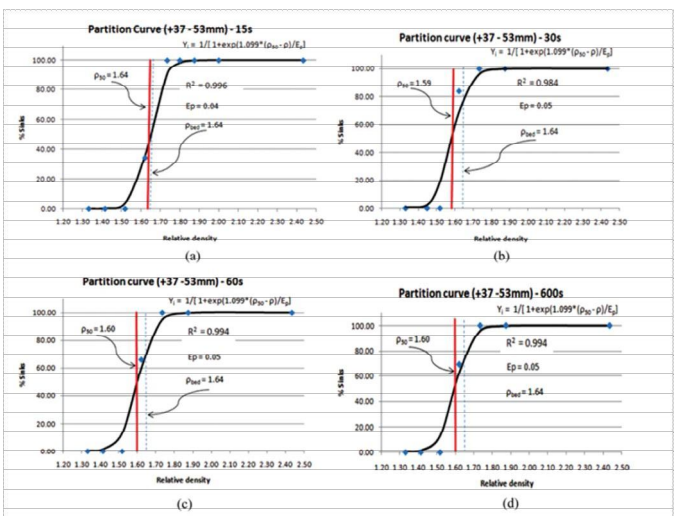

Fig2. Partition curves for +37–53mm particles at time intervals

B. *Effect of Particle Size on Coal Separation*

The variation of Ep and ρ_{50} with time plots for the different particle size ranges shown in Figures 3 and 4, respectively, were used to evaluate the separation performance of the dry air fluidized bed From Figure 4, it can be observed that the particle size has a significant effect on the separation performance of the fluidized bed. Generally, the big particles tend to separate faster and more efficiently than the smaller particles. The observed trend in Figure 3 indicates that within 20 seconds, the +37–53mm particles had completely separated, followed by the +22–31.5mm particles that took approximately 25 seconds. Low Ep values of 0.05 were recorded for the separation of both +37–53mm and +22–31.5mm particles.

This means that the air fluidized bed can be used to efficiently separate the above mentioned particles size ranges. However, the separation performance of the +37–53mm can be further improved by using a bed height deeper than 40 cm as a fluidized bed. A bed height of ≤ 400mm does not provide enough space for effective beneficiation of >50mm coal [6]. Although, the Ep values of the +9.5–16mm particles improved with time, the values recorded during the first 50 seconds were always higher than those of all the other particle size ranges outlined above. This shows that a relatively longer separation time is required for the efficient separation of the +9.5–16mm particles as compared to the +16–22 mm, +22–31.5 mm, and +37–53mm particles. On the other hand, the separation of the +16–22mm Blk particles was associated with an average Ep value of about 0.07, which is lower than the average Ep for the +9.5–16mm particles, but higher than the average Ep of the +22–31.5mm and +37–53mm particles.

The performance of the fluidized bed separator was also assessed based on the cut density shift as illustrated in Figure 4. The results in Figure 4 show that the cut densities of the +9.5–16mm and +16–22mm Blk particles shifted to above the initial cut density of 1.64 whilst the cut densities of the +22–31.5mm and +37–53mm particles shifted to slightly below 1.64. The shift in the cut densities can be attributed to the balance of the forces that act on the particles in a fluidized bed. These forces include drag, buoyancy force, and gravitational force as highlighted in Equation 2. The near cut density particles have got rise/settling velocities close to zero; hence, the motion of the particles can be easily influenced by the circulation forces associated with the operation of the fluidized bed. This can result in the misplacement of the particles as they end up reporting either to the sinks or floats regardless of their specific densities. Although relatively constant cut densities were achieved for the separation of the +22–31.5mm and +37–53mm particles, the fact that after 30 seconds the cut densities were below the initial bed density of 1.64 indicates that some near cut density float particles were misplaced during the separation process. The +22– 31.5mm and +37–53mm particles have got wider surface areas as compared to the +9.5–16mm and +16–22mm Blk particles and are more prone to the particle-loading mechanism resulting in the increased apparent weight of the near cut density float particles, which will end up reporting to the sinks. On the other hand, the +9.5–16mm and +16–22mm Blk near cut density sink particles are probably more susceptible to the low settling or rise velocity mechanism resulting in the observed trend in Figure 4.

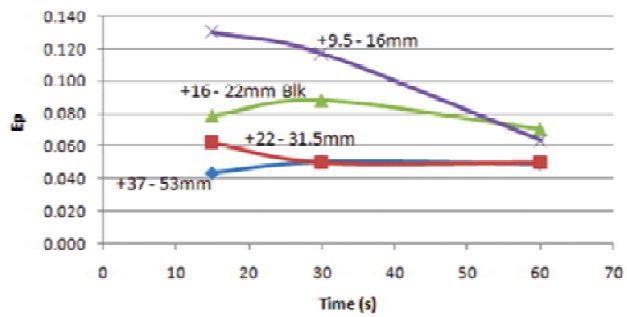

Fig3. Ep vs. time for the different particle size ranges

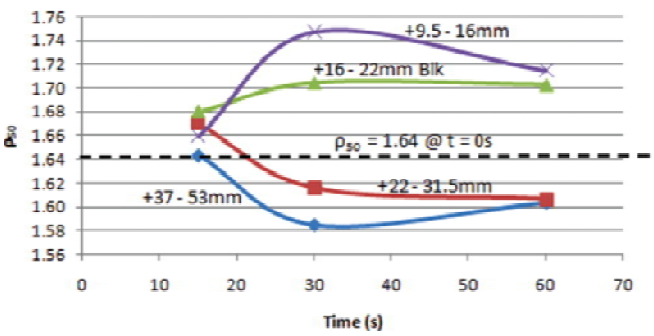

Fig4. ρ_{50} vs. time for the different particle size ranges

C. *Effect of Particle Shape on Coal Separation*

The effect of the particle shape on the performance of the three-dimensional fluidized bed was investigated using the +16–22mm particles of different shapes namely the blockish (Blk), flat (FB), and sharp-pointed prism (SR) particles. Figure 5 illustrates how the Ep values of the +16–22mm particles of three different shapes varied with time. The blockish particles separated better than flat and sharp-pointed particles as evidenced by the relatively low and constant Ep values obtained after about 30 seconds of separation. Although relatively constant Ep values were achieved for separation of +16–22mm SR, high average Ep values of approximately 0.10 were recorded. On the other hand, the Ep values of the +16– 22mm FB particles improved with time, but the continuous shift of the cut density makes it difficult to efficiently separate the flat particles. Flatter partition curves were obtained during the early stages of the separation of all the +16–22mm and this can be attributed to the high Ep values.

Figure 6 illustrates how the q50 of the +16–22mm Blk, +16–22mm SR, and +16–22mm FB particles varied with time. The difference in the observed trends of the cut densities of the +16–22mm particles of different particle shapes highlights that particle shape is one of the parameters that has a significant effect on the separation performance of the fluidized bed and as such, different optimum operating conditions should be used for the efficient separation of different particle shapes. The dynamic cut densities of the blockish particles fluctuated above the initial cut bed density of 1.64, with an average cut density of 1.70 being attained under steady state conditions. This means that some of the particles that could have been recovered as sinks short circuited into the floats stream probably due to the low settling or rise mechanism as explained above. On the other hand, the cut density of the flat particles fluctuated from 1.62 after 15 seconds to 1.50 after 60 seconds whilst the cut density of the sharp-pointed prism shifted from 1.69 after 15 seconds to 1.55 after 60 seconds (see Figure 6).

Although relatively lower Ep values were obtained with flat particles than those obtained for the separation of the sharp-pointed particles, the continuous shift of the cut density makes it difficult to efficiently separate the flat particles. Both the flat and the sharp-pointed particles have wide surface areas in contact with the pseudo-fluid and are more prone to the particle-loading mechanism. This alters the apparent weight of the particles resulting in the misplacement of the near cut density material as the particles with a density slightly less than that of the medium end reporting to the sinks stream.

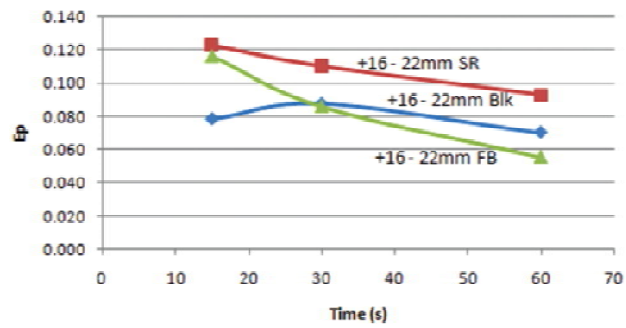

Fig5. Ep vs. time for the +16–22mm of different shapes

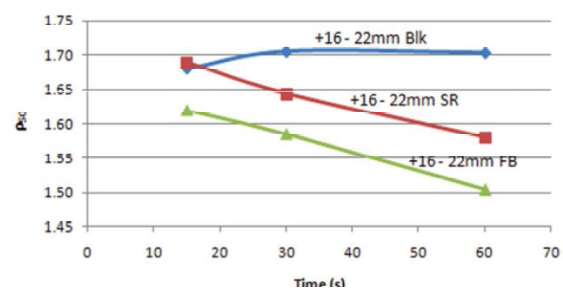

Fig6. ρ_{50} vs. Time for the +16–22mm of different shapes

V. Conclusion

The study on the effects of particle size, density, and shape on the performance of a dry air fluidized bed revealed some critical information that is expected to go a long way in the further development of a more efficient dry air fluidized bed separators. Generally, the bigger particles, that is the +37–53mm and +22–31.5mm particles, separated faster and more efficiently than the smaller particles: +16–22mm and +9.5–16mm. Average Ep values as low as 0.05 were recorded for

the separation of+37–53mm and +22–31.5mm particles under steady state conditions with minimum fluctuation of the cut density. However, a further decrease in the particle size was associated with relatively high Ep values and a continuous shift of the cut density The laboratory fluidized bed can efficiently separate the +16–22 mm, +22–31.5 mm, and +37–53mm particles and the separation efficiency of the particles can be further improved by using deeper beds (bed height ≥ 40 cm).. Although the +37–53mm and +22–31.5mm particles can be efficiently separated using the same bed, separate beds with different optimum operating parameters would be required for the efficient separation of the +16–22mm and +9.5–16mm particles, respectively. This further illustrates that prescreening of the coal particles into relatively narrow ranges is important in the optimization of dry coal beneficiation using a dry air fluidized bed.

Particle shape is a very difficult parameter to control, but the separation results of the +16–22mm of different shapes indicate that particle shape has got a significant effect on the separation performance of the particles in the air fluidized bed. Three different particle shapes that were used during the tests included the flat, blockish and sharp-pointed prism particles. The blockish particles that have the smallest surface area to volume ratio and hence are less subject to medium viscosity effects separated better than flat and the sharp-pointed particles as evidenced by the relatively low and constant Ep values obtained after about 30 seconds of separation. Despite relatively constant Ep values being achieved for the separation of prism particles, high average Ep values of approximately 0.10 were recorded. On the other hand, the Ep values of the flat particles improved with time, but the continuous shift of the cut density made it difficult to efficiently separate the flat particles.

Particles of different sizes, shapes, and densities interact with the separating medium/fluid in various ways and the resultant rise/settling velocities of the near cut density particles have a significant effect on the separation performance of the air fluidized bed coal separator. In as much as the air fluidized bed behaves like a pseudo-fluid, some medium particles can always accumulate on the surfaces of the particles thereby altering their apparent densities. This has a negative effect on the separation performance of the near cut density float particles as they end up recovered as sinks. The amount of medium particles that accumulate on the surfaces of the particles is directly linked to the surface area of the particle in contact with the fluid. The above conclusion further illustrates the importance of particle size, shape, and density on the separation performance of particles in the dry air fluidized bed.

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