Separation performance of raw coal from South Africa using the dense gas-solid fluidized bed beneficiation technique

by J. He*, Y. Zhao*, Y. He*, Z. Luo*, C. Duan*

Synopsis

The separation performance of a raw coal sample from South Africa based on the dense gas-solid fluidized bed beneficiation technique was investigated. Analysis showed that the raw coal sample distributes mainly in the -50+6 mm size range with the -1.6 g/cm³ density fraction accounting for 78.20% of the cumulative mass distribution. A flow sheet of the sequential coal beneficiation technique was introduced. The experimental and simulation results of the hydromechanical and density distribution stability indicate that the dense gas-solid fluidized bed could provide a stable separation environment with uniform density fluctuations under suitable operating conditions. With the application of this technique on the raw coal sample, the separation results show that three products, consisting of 73.25% clean coal with an ash content of 9.59%, 11.31% middlings, and 15.44% gangue were effectively separated at two different densities of 1.82 g/cm³ and 1.57 g/cm³. This study provides an effective flow sheet for achieving the high-efficiency separation performance on raw coal from arid areas.

Keywords
dense gas-solid fluidized bed, dry coal beneficiation, density distribution, separation efficiency.

Introduction

The development of coal preparation technology is important to achieve the high-efficiency utilization of coal resources, and is also beneficial regarding energy saving and emission reduction. Techniques and equipment based on wet beneficiation, such as hydraulic jigging, dense medium cyclone, and flotation have been widely adopted in the field of coal beneficiation (Fourie, Van Der Walt, and Falcon, 1980; Chen *et al.*, 2012; Song and Valdivieso, 1998; Jia, Harris, and Fuerstenau, 2002; Cao *et al.*, 2012. However, most remaining global coal resources are found in arid and water-stressed regions, including the midwest of the USA, south-east India, the Ruhr of Germany, and especially in South Africa and China's central and western regions. The proved coal reserves in Xinjiang (a water shortage province), China are 2190 billion tons, which accounts for 40% of the entire coal reserves in China. South Africa's coal reserves are 206 billion tons, which accounts for two-thirds of the reserves in the whole of Africa. The proved coal reserves in South Africa are 58.75 billion tons (Jeffrey, 2005; Hartnady, 2010; Wagner and Tlotleng, 2012), and raw coal production is approximate 300 Mt/a, making the country Africa's foremost coal producer. Wet coal beneficiation techniques are not applicable to these countries and regions, and it is therefore necessary to develop and apply dry beneficiation technologies to achieve efficient utilization of these coal resources (Dwari and Rao, 2007; Sahu, Biswal, and Parida, 2009).

Gas-solid fluidization techniques have been widely applied in the fields of chemical engineering, combustion, materials separation, etc. (Kunii and Levenspiel, 1991). The dense gas-solid fluidized bed separator applied in coal beneficiation has some characteristics similar to the bubbling fluidized beds utilized in chemical engineering, but also some essential differences. The dense gas-solid fluidized bed separator with high densities needs to provide a favourable density distribution environment for coal beneficiation through some special flow properties and interaction between the gas and solid phases. A few scientists from countries such as the USA, Canada, Germany, Japan, South Africa, the Netherlands, Brazil, and China have carried out a series of investigations to develop dry coal beneficiation techniques based on dense gas-solid fluidized beds (Tanaka *et al.*, 1996; Oshitani *et al.*, 2003; Dong and Beeckmans, 1990). China University of Mining and Technology has contributed to research on the fundamental separation theory and engineering application of dense gas-solid fluidized bed beneficiation techniques since

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the 1980s, and has made considerable progress (Chen and Yang, 2001; Zhao, Luo, and Chen, 2004; Zhao *et al.*, 2010; Luo *et al.*, 2006; Luo, Chen, and Zhao, 2002; Luo and Chen, 2001a, 2001b; He *et al.*, 2005; Luo and Zhao, 2002; Zhao *et al.*, 2010).

Based on the previous separation theory and beneficiation technique, a type of sequential coal beneficiation technique that could effectively separate raw coal into three products (cleaning coal, middling, and gangue) by density has been proposed and applied on a semi-industrial scale. This technique utilizes two different types of separating medium to achieve different separating densities. It avoids the limitation of previous equipment, which could produce only two products (cleanings and tailings). The technique constitutes a novel approach to the continuous beneficiation of coal, which shares similar characteristics with the wet dense medium cyclone separation technique for three products.

A raw coal sample from CDW Enterprise of South Africa was used to carry out separation experiments with the new sequential coal beneficiation technique. The separation performance is analysed and discussed using a combination of experimental work and numerical simulation.

Experimental

Materials

Coal basic properties

The coal properties were analysed firstly. The sample had a low moisture content of 2.12%, an ash content of 23.88%, a volatile component of 26.42%, a medium sulphur content of 1.26%, and a high heat productivity of 29.50 MJ/kg.

Particle size distribution

A coal sample of approximate 1000 kg was sieved for the analysis of particle size distribution. The detailed particle size distribution is shown in Table I. The analytical results were as follows.

➤ The coal mass distribution in the +50 mm fraction is 8.12%, with an ash content of 45.51%. This shows that the coal content of the large size fraction is lower, but the ash content is higher, which indicates that the gangue occurs mainly in this size range
➤ The mass distribution in the -50+25 mm, -25+13 mm, and -13+6 mm fractions is 49.42%, 21.36%, and 12.06% respectively. The coal content of the -50+25 mm size is the largest, accounting for nearly one half of the entire coal sample. The total mass distribution in the -50+6 mm size coal accounts for 82.84%, with an ash content of 23.72%. This indicates that the size range of -50+6 mm is the dominant particle size distribution of raw coal
➤ The total mass distribution of -6 mm size coal is 9.04%, with an ash content of 17.36%. This demonstrates that the content of -6 mm size coal is less, with a lower ash content than the raw coal.

Density component

The +50 mm fraction was crushed to -50 mm. Float-sink experiments were carried out on the -50+25 mm, -25+13 mm, -13+6 mm, -6+3 mm, and -3+0.5 mm fractions. The final float-sink results are summarized in Table II. The analytical results for the density component were as follows.

➤ The lower-density fraction of the coal sample is the largest. The dominant density distribution is 1.3–1.4 g/cm^3, with a mass distribution of 43.23% and an ash content of 6.80%. This indicates that the ash content of the lower-density producti is lower, which is propitious for obtaining high-quality cleaning coal
➤ The cumulative mass distribution in the fractions with a density of -1.6 g/cm^3 accounts for 78.20%, with a cumulative ash content of 9.86%. Therefore, the recovery of cleaning coal could be increased if the required ash content is set below 10%
➤ The mass distribution in the fractions with a density of 1.6–1.8 g/cm^3 is less than that of the lighter fractions. Hence it will be necessary to control the separating density at around 1.6–1.8 g/cm^3 in order to achieve a good separation efficiency with a lower mismatch rate
➤ The mass distribution in the fraction with density of +1.8 g/cm^3 accounts for 15.46% of the total, with an ash content of 73.28%. This indicates that the higher-density fraction of the sample has a medium coal content with a higher ash content. It will therefore be necessary to separate the high-density gangue from raw coal in the first step of this dry beneficiation technique
➤ The content of float-sink coal slurry is 1.09% with an ash content of 31.42%, which is higher than the ash content of raw coal. This demonstrates that the gangue

Table I

Particle size distribution of raw coal sample

Size range (mm)	Weight (kg)	Distribution (%)	Quality index	
			Ash content (%)	Moisture content (%)
+50	82.45	8.12	45.51	2.18
-50+25	498.22	49.42	24.25	2.33
-25+13	215.34	21.36	23.62	2.38
-13+6	121.53	12.06	21.74	2.45
-6+3	41.36	4.11	19.22	2.21
-3+0.5	28.44	2.83	16.81	2.48
-0.5	21.08	2.10	14.48	2.52
Total	1008.42	100.00		

Table II

The final float-sink results for the -50+6 mm size fraction

Density (g/cm³)	Distribution (%)	Ash content (%)	Accumulation				Separating density δ±0.1	
			Floats		Sinks		Density	Recovery
			Mass distribution (%)	Ash content (%)	Mass distribution (%)	Ash content (%)	(g/cm³)	(%)
-1.3	2.30	3.47	2.30	3.47	100.00	21.61	1.3	45.52
1.3–1.4	43.23	6.80	45.53	6.63	97.70	22.03	1.4	67.96
1.4–1.5	24.74	13.48	70.27	9.04	54.47	34.12	1.5	32.66
1.5–1.6	7.93	23.07	78.20	9.86	29.73	51.29	1.6	12.33
1.6–1.7	4.41	30.41	82.61	11.53	21.80	61.54	1.7	6.34
1.7–1.8	1.93	38.50	84.54	12.15	17.39	69.42	1.8	9.67
+1.8	15.46	73.28	100.00	21.61	15.46	73.28		
Total	100	21.61						
Coal slurry	1.09	31.42						
Total	100	21.96						

appears the performance of degradation in water. Thus the dry beneficiation technique using the dense gas-solid fluidized bed is adequate for the whole separation process.

Figure 1 shows the washability curves of the raw coal sample, which are composed of an elementary ash curve, a cumulative floats curve, a cumulative sinks curve, a density curve, and a near-density curve. If the required ash content of cleaning coal is less than 13% or 10%, the recovery of cleaning coal could theoretically achieve nearly 85.00% or 75.00% at a separating density of 1.84 g/cm³ or 1.59 g/cm³, and the δ±0.1 content appears to be 9% or 15% after removing the gangue. The performance indicates that the recovery of cleaning coal decreases, and the washability of raw coal drops, as the quantity of cleaning coal increases. Based on the above analysis, a two-stage continuous beneficiation technique based on the dense gas-solid fluidized bed should be utilized in order to obtain pure cleaning coal with an ash content of less than 10% effectively. The detailed beneficiation flow sheet is introduced in Figure 2.

Properties of fluidizing media

Magnetite powder provided by the iron mine plant of Panzhihua, China was selected as the basic fluidizing medium. After preparation by grinding and sieving using an experimental-scale globe mill and grading screen, magnetite powders with a particle size distribution of -0.3+0.15 mm and -0.15+0.074 mm were employed as fluidizing media in the two-stage beneficiation process. The magnetic material contents of the magnetite powders are 99.85% and 99.86% respectively, and their bulk densities 2.55 g/cm³ and 2.41 g/cm³. This demonstrates that the qualities of the magnetite powders are good, which is favourable for the formation of a stable fluidization environment and separating density distribution for coal beneficiation.

Experimental set-up

A flow sheet of the sequential coal beneficiation technique based on the dense gas-solid fluidized bed is illustrated in Figure 2. The entire flow sheet consists essentially of raw coal pre-treatment (crushing, air drying, and screening), two-stage coal separation, magnetite powder recovery, and solid medium recovery.

Firstly, raw coal was crushed to the particle size range of -50 mm, and completely dried through the air drying system before separation. Raw coal of -50+6 mm was selected as the feed material for separation by screening. Raw coal with a particle size range of -6 mm was collected as fine coal. In the following step, -50+6 mm raw coal was supplied to the dense gas-solid fluidized bed separator as feedstock. In the first separation stage, the -0.3+0.15 mm magnetite powder was mixed with -1 mm fine coal uniformly in proportion as fluidized medium. Under suitable operating conditions, complete and stable fluidization conditions are formed in the separator with a certain bed expansion height and density distribution. Thus, raw coal is separated according to density difference based on Archimedes' Law, with lighter coal floating and denser coal sinking. As a result, the high-density gangue was separated from raw coal, and the low-density mixed coal was obtained in the first separation stage.The low-density mixed coal was then fed into the second dense gas-solid fluidized bed separator for further purification. A uniform mixture of -0.15+0.074 mm magnetite powder and -1 mm fine coal was used as the fluidized medium in this stage. Finally, the mixed coal

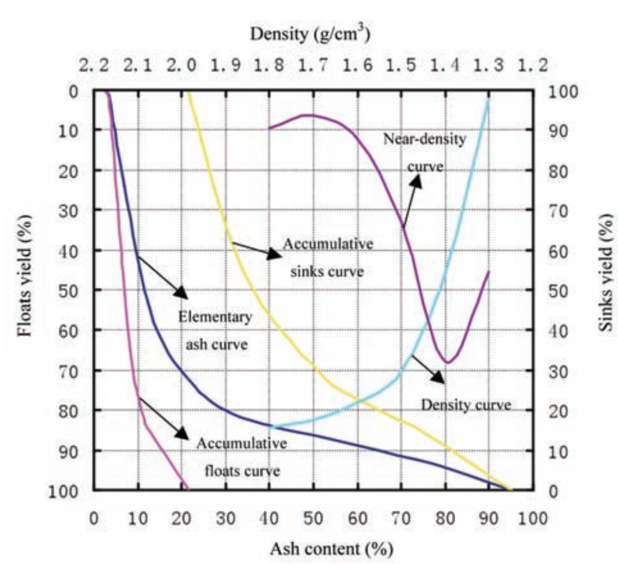

Figure 1—Washability curves for raw coal sample

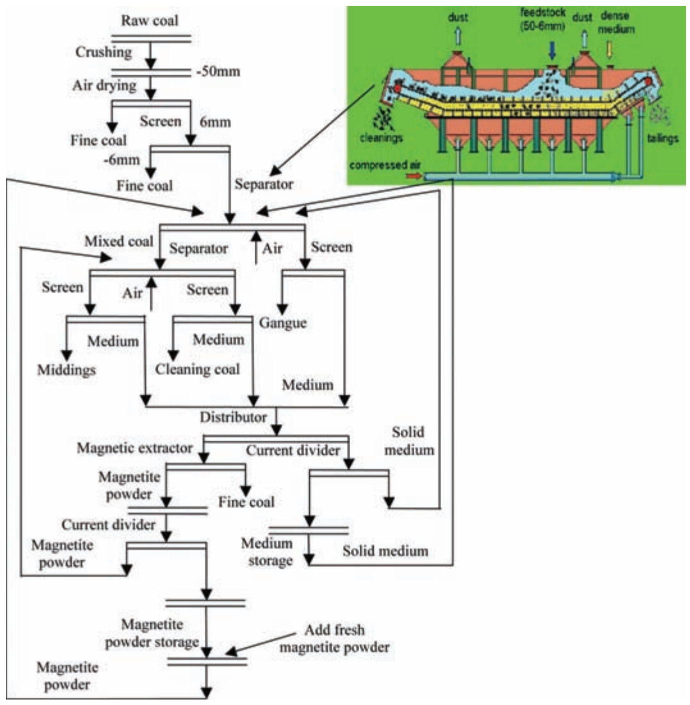

Figure 2—Flow sheet of the sequential coal beneficiation technique based on the dense gas-solid fluidized bed

stratified and segregated by density with cleaning coal floating and the middlings sinking. The pure cleaning coal was obtained after the second separation stage. The final products of the two-stage sequential coal beneficiation technique were cleaning coal, middlings, and gangue.

In addition, a recovery system for the fluidized medium was introduced to achieve high-efficiency recycling and utilization of magnetite powder. A certain amount of fluidized medium was collected through a screening process after separation, which aims to remove the adhesional medium from the particle surfaces of different products. The recycling fluidized medium was divided into two parts. One part was fed into a magnetic separator to obtain pure magnetite powder from the mixed fluidized medium, and the other part was also divided by a current divider for different purposes. The purpose of this was to maintain uniform fluidization and a stable density distribution in the fluidized bed separator. However, fine coal accumulated continuously in the separation stages, which had a major influence on bed density distribution. Too high or too low a content of fine coal could result in obvious fluctuations in bed density, which has an adverse effect on coal separation efficiency. Therefore, a bed density adjusting and controlling system was developed to achieve the dynamic adjusting of separation density. The magnetite powder and solid medium after purification and division could be returned immediately into the dense gas-solid fluidized bed separator according to the separation requirements.

The results of the continuous separation experiments indicate that the flow sheet for the sequential coal beneficiation technique based on dense gas-solid fluidized bed has the advantages of high separation efficiency, low operating cost, simplicity, and less environment pollution. It constitutes a novel beneficiation technique for coal separation and utilization in arid areas and water-stressed countries.

Results and discussion

Hydromechanical stability of dense gas-solid fluidized bed

It is very important to maintain the hydromechanical stability of the dense gas-solid fluidized bed in order to provide a stable separation environment for coal beneficiation. The expansion height, void fraction, and pressure drop are the major parameters used to evaluate the stability of the fluidized bed. The combined approach of experimental measurement and numerical simulation was used to verify the hydromechanical characteristics of the fluidized bed. The numerical simulation was carried out using Fluent 13.1 computational fluid dynamics (CFD) software.

An experimental-scale fluidized bed was utilized to validate the stability in its three-dimensional separation space. Real-time information on bed expansion heights could be measured and recorded with a dynamical measuring scale. The average void fraction of the fluidized bed could be calculated from the values of the bed's degree of expansion. The bed expansion heights and void fractions obtained experimentally and through simulation are compared in Figure 3. The results show that the bed height and void fraction basically bear a linear relationship to increasing superficial gas velocity. The bed height varies mainly in the range of 105–122 mm, and the void fraction between 0.30 and 0.45. The expansion characteristics of the fluidized bed indicate that obvious bed fluctuations, intense bubbling and slugging performance, and other adverse fluidization conditions do not occur within the suitable range of operating gas velocity.

Figure 4 shows the relationship of the bed pressure drop to superficial gas velocity at static bed heights H_s of 25 mm, 50 mm, 75 mm, 90 mm, and 110 mm. The pressure drops

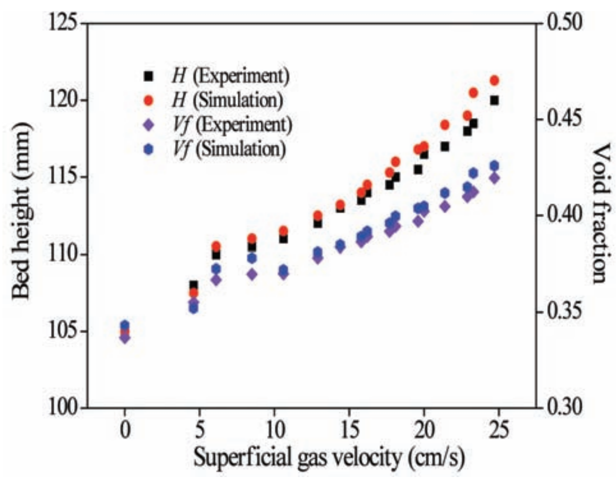

Figure 3—Expansion characteristics of the dense gas-solid fluidized bed

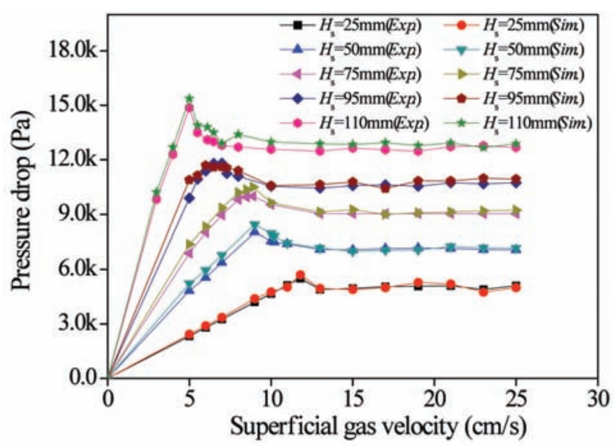

Figure 4—Bed pressure drop across the dense gas-solid fluidized bed

across the fluidized bed at different heights were measured with a U-tube manometer. It can be seen that the bed pressure drop changes linearly with increasing gas velocity when the superficial fluidizing velocity is low. The higher the static bed height, the greater the linear slope, which indicates that the pressure drop increases with bed height. When the superficial gas velocity reaches the minimum fluidization velocity for the fluidized bed, the peak value of pressure drop could be obtained. With continuously increasing gas velocity, the pressure drops fall slowly to a stable value. The fluctuations in overall pressure drop then decrease, which accords with the requirement for the stability of bed pressure drop. Thus the results show that the pressure drops across the dense gas-solid fluidized bed at different static bed heights are very stable. These results therefore demonstrate that the dense gas-solid fluidized bed has favourable fluidization stability characteristics and a uniform distribution of solid-phase particles. Indirectly, this explains why the rising bubbles with a well-distributed size range display steady kinetic behaviour in the fluidization, which provides the high-quality initial environment for coal beneficiation by density.

Density distribution stability of dense gas-solid fluidized bed

Raw coal is separated in the dense gas-solid fluidized bed, with lighter products floating and denser products sinking according to their density differences. The density distribution stability is therefore a crucial factor in achieving high-efficiency beneficiation of raw coal with the fluidized bed. The experimental measurements and numerical simulations were also combined to verify the bed density distribution and fluctuation in two beneficiation stages.

For the first stage, Figure 5 shows the simulation results of the density fluctuation in a fluidized bed with the mixture of -0.3+0.15 mm magnetite powder and -1 mm fine coal as the fluidized medium. It can be seen that the bed densities exhibit stable fluctuations around 1.85 g/cm3 at different bed heights (H_f). The mean bed densities are calculated as 1.88 g/cm3, 1.82g/cm3, and 1.85 g/cm3, with standard deviations of 0.14 g/cm3, 0.13 g/cm3, and 0.14 g/cm3 at H_f = 0.35 m, 0.75 m, and 1.05 m respectively. The simulation results show that the mean bed densities are distributed mainly between 1.80 g/cm3 and 1.90 g/cm3, with standard deviations less than 0.15 g/cm3. This obviously indicates that the bed density distributions are very uniform with stable fluctuations. This kind of density distribution in a dense gas-solid fluidized bed is more propitious for removing high-density gangue from raw coal in the first beneficiation stage. In experimental measurements, a static measurement method of bed density was applied to obtain the density distribution at different bed heights. Four measurement points (designated 1, 2, 3, and 4) were designed and arranged at different positions in the same plane surface in the internal space of the three-dimensional fluidized bed. The bed densities at these four points were measured with a group of gradiomanometers. The mean density at the same height was then calculated by a mean value approach. The standard deviation S_ρ of the density distribution was also calculated (Equation [1]):

$$S_\rho = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\rho_i - \bar{\rho})^2} \qquad [1]$$

where ρ refers to the bed density of point i, $\bar{\rho}$ refers to the mean bed density of all points, and N is the total number of measurement points. The comparison of the experimental results and simulations is shown in Table III. The experimental results show that the mean bed densities at different measurement points are close to 1.84 g/cm3 with a standard deviation S_ρ of 0.0147 g/cm3. It can be seen that the simulation results agree very well with the experimental results.

For the second stage, Figure 6 shows the simulation results for the density fluctuation with the mixture of -0.15+0.074 mm magnetite powder and -1 mm fine coal as fluidized medium. It can be seen that the bed densities also appear stable around 1.60 g/cm3 at different bed heights (H_f). The mean bed densities are calculated as 1.59 g/cm3, 1.62 g/cm3, and 1.61 g/cm3, with standard deviations of 0.11 g/cm3, 0.09 g/cm3, and 0.10 g/cm3 at H_f = 0.35 m, 0.75 m, and 1.05 m respectively. The simulation results show that the mean bed density is distributed mainly between 1.59 g/cm3

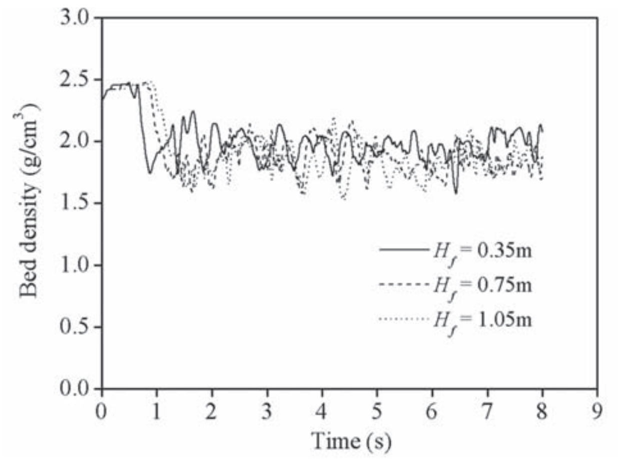

Figure 5–Density fluctuation at different bed heights (first beneficiation stage)

Table III

Comparison of experimental and simulated densities (first beneficiation stage)

Bed height (m)	Bed density ρ (g/cm³)				
	Experiment value				Simulation value
	Point 1	Point 2	Point 3	Point 4	
0.15	1.82	1.83	1.86	1.82	1.84
0.35	1.84	1.82	1.85	1.84	1.88
0.75	1.81	1.85	1.83	1.86	1.83
1.05	1.88	1.83	1.87	1.82	1.85
$\bar{\rho}$	1.84	1.83	1.85	1.84	1.85
$S\rho$	0.0147				--

and 1.62 g/cm3, with standard deviations less than 0.12 g/cm3. Figure 6 also indicates that the bed density distributions are very uniform with stable fluctuations. The density distributions of the fluidized bed provide a suitable separation environment for obtaining pure cleaning coal and middlings in the second beneficiation stage. The experimental measurements of bed densities were conducted using the same approach as for the first separation stage. The comparison of experimental and simulation results is shown in Table IV. The results show that the mean bed densities at different measurement points are close to 1.59 g/cm3 with a standard deviation S_ρ of 0.0125 g/cm3. The simulation results correspond well with the experimental results.

Separation performance of raw coal sample from South Africa

The flow sheet of the sequential coal beneficiation technique based on the dense gas-solid fluidized bed was applied in the experimental separation of raw coal sample from South Africa. The washability analysis of the raw coal indicated that the separating densities need to be controlled around 1.84 g/cm3 and 1.59 g/cm3 for a high recovery of cleaning coal with an ash content below 10%. The experimental float-sink results for the products of two beneficiation stages are summarized in Tables V and VI. The partition curves of raw coal are shown in Figure 7. The value of δ equals to ρ50, representing the effective separating density in the dense gas-solid fluidized bed separator. The probable error E = (ρ50-ρ50)/2 represents the separating efficiency of the fluidized bed separator. A lower *E* value indicates a more effective separation.

The gangue (15.44% of the feed by mass, and ash content of 72.13%) was rejected in the first beneficiation stage at a high separating density of 1.82 g/cm3. The probable error *E* equals 0.07 g/cm3, which indicates that the gangue in raw coal sample was effectively removed at a suitable separating density. In the second sequential beneficiation stage, the recovery of cleaning coal was 73.25%, with an ash content of 9.59%, at a low separating density of 1.57 g/cm3. The probable error *E* equals 0.05 g/cm3 and the recovery efficiency was 97.97%, indicating favorable separation performance. In summary, three products consisting of 73.25% pure cleaning coal with an ash content below 10%, 11.31% middlings, and 15.44% gangue were effectively separated from the raw coal sample. These results demonstrate that this technique of sequential coal beneficiation yields the similar separation products and efficiency to the wet beneficiation flow sheet for raw coal.

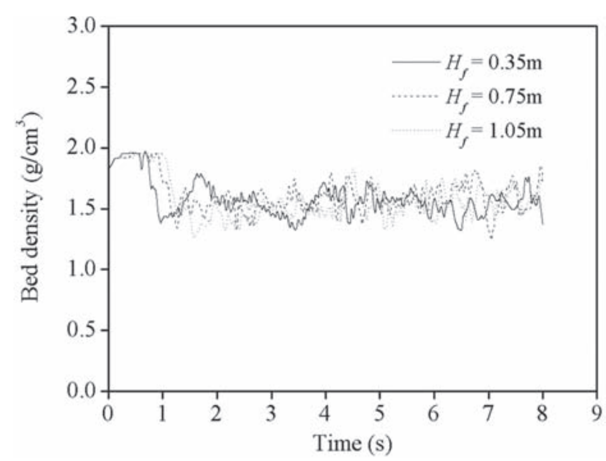

Figure 6—Density fluctuation at different bed heights (second beneficiation stage)

Table IV

Comparison of experimental and simulated densities (second beneficiation stage)

Bed height (m)	Bed density ρ (g/cm³)				
	Experiment value				Simulation value
	Point 1	Point 2	Point 3	Point 4	
0.15	1.59	1.58	1.56	1.58	1.60
0.35	1.57	1.59	1.61	1.56	1.59
0.75	1.61	1.60	1.59	1.58	1.62
1.05	1.58	1.62	1.59	1.60	1.61
ρ	1.59	1.60	1.59	1.58	1.61
S_ρ	0.0125				--

Table V

Float-sink experimental results for -50+6 mm coal separation in the first beneficiation stage

Density range (g/cm3)	Mixed coal (%)			Gangue (%)			Calculated feedstock (%)	Partition coefficient (%)
	O	O/F	Ash content	O	O/F	Ash content		
-1.30	2.72	2.30	3.36	0.00	0.00	3.47	2.30	0.00
1.3-1.4	51.12	43.23	6.77	0.00	0.00	3.80	43.23	0.00
1.4-1.5	29.19	24.68	13.42	0.39	0.06	13.55	24.74	0.24
1.5-1.6	9.17	7.75	22.95	1.17	0.18	23.28	7.93	2.27
1.6-1.7	3.16	2.67	30.77	1.49	0.23	31.79	2.90	7.93
1.7-1.8	2.91	2.46	39.42	6.35	0.98	40.94	3.44	28.49
+1.80	1.74	1.47	76.56	90.61	13.99	75.86	15.46	90.49
Total	100.00	84.56	13.02	100.00	15.44	72.13	100.00	

Table VI

Float-sink experimental results for -50+6 mm coal separation in the second beneficiation stage

Density range (g/cm3)	Cleaning coal (%)			Middlings (%)			Calculated feedstock (%)	Partition coefficient (%)
	O	O/F	Ash content	O	O/F	Ash content		
-1.30	3.14	2.30	3.42	0.00	0.00	3.43	2.30	0.00
1.3-1.4	58.50	42.85	6.58	3.36	0.38	3.89	43.23	0.88
1.4-1.5	31.60	23.15	12.68	13.53	1.53	14.03	24.68	6.20
1.5-1.6	5.90	4.32	22.64	30.33	3.43	24.56	7.75	44.26
1.6-1.7	0.63	0.46	30.51	19.54	2.21	33.87	2.67	82.77
1.7-1.8	0.19	0.14	38.92	20.51	2.32	41.25	2.46	94.31
1.80	0.04	0.03	72.47	12.73	1.44	78.92	1.47	97.96
Total	100.00	73.25	9.59	100.00	11.31	34.60	84.56	

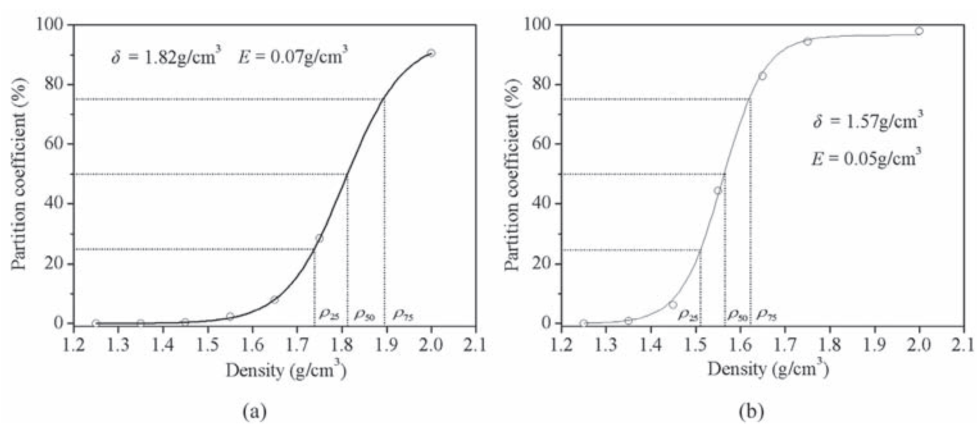

Figure 7—Partition curve of products at (a) high separating density; (b) low separating density

Conclusions

The following major conclusions can be drawn from the study.

1. The particle size distribution and density analysis of the raw coal sample from South Africa show that the -50+6 mm size range is the dominant particle size, with 78.20% of the raw coal in the density fraction -1.6 g/cm3. The washability results indicate that the theoretical separating density should be adjusted to around 1.84 g/cm3 and 1.59 g/cm3 in the first and second beneficiation stages respectively, in order to increase the recovery of cleaning coal and remove the gangue effectively
2. The results of experimental measurement and numerical simulation show that the bed height varies mainly in the range of 105-122 mm, and the void fraction between 0.30 and 0.45. The bed pressure drops at different bed heights maintain stable fluctuations after steady fluidization. This indicates that hydromechanical stability can be achieved with a suitable fluidized medium and operating conditions
3. The bed densities show stable fluctuations around 1.85 g/cm3 and 1.60 g/cm3 at different bed heights, with standard deviations of less than 0.15 g/cm3 and 0.12 g/cm3 in the first and second beneficiation stages respectively. This indicates that the bed density distributions in the dense gas-solid fluidized bed separator

are very uniform. The separator provides a stable density environment for the effective separation of raw coal

4. Three products consisting of 73.25% pure clean coal with an ash content of 9.59%, 11.31% middlings, and 15.44% gangue were effectively separated from raw coal at a high density of 1.82 g/cm³ and a low density of 1.57 g/cm³. The separation performance indicates that this technique of sequential coal beneficiation based on dense gas-solid fluidized bed has good separation efficiency for the raw coal sample from South Africa.

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