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DRY BENEFICIATION AND CLEANING OF CHINESE HIGH-ASH COARSE COAL UTILIZING A DENSE-MEDIUM GAS-SOLID FLUIDIZED BED SEPARATOR

Jingfeng HE[*,], Mingbing TAN[*], Ran ZHU[*], Zhenfu LUO[**]**

[*] School of Chemical Engineering and Technology, China University of Mining and Technology, Xuzhou 221116, China; jfhe@cumt.edu.cn

[**] Key Laboratory of Coal Processing and Efficient Utilization of Ministry of Education, China University of Mining and Technology, Xuzhou 221116, China

Abstract: Dry dense-medium fluidized bed separation provides a new alternative approach for coal beneficiation and cleaning. An indicator of segregation degree S_{ash} was proposed to evaluate the stratified performance of coal samples by bed density. Fluidization stability of the bed was greatly enhanced by mixing a certain amount (21.53%) of fine magnetite powder (< 0.15 mm) into the fluidized media, which indicated a uniform density distribution as well as slight fluctuations in bed. It was found that the favorable density-segregation performance of 3–13 mm coarse coal occurred with a static bed height of 80 mm and a superficial gas velocity of 11.84 cm/s. The optimal segregation degree values of 0.67, 0.74 and 0.76 were obtained for 3–6, 6–10 and 10–13 mm coal samples, respectively. Low-ash clean coal with yields of 50.79, 56.83 and 61.24% were effectively acquired by the dry separation for various coal size fractions, respectively. Probable error values of 0.07, 0.055 and 0.05 g/cm^3 were achieved, indicating good separation performance.

Keywords: *coal cleaning, dense-medium fluidized bed, density distribution, segregation, separation performance*

Introduction

Coal resource has been playing a significant role in the fields of energy consumption and utilization in the past few decades. However, it also brings serious environment pollution due to coal firing and pollutant emissions. Coal beneficiation has been recognized as an efficient approach to achieve coal cleaning by the desulfurization and ash reduction, which reduces environment pollution by decreasing the emissions of CO_x, SO_x etc. (Zhao et al., 2011).

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Dry coal beneficiation technology utilizing a dense-medium gas-solid fluidized bed has drawn worldwide attention and developed rapidly in the past few years. It has the advantages of low investment cost, no water-use, high separation efficiency, wide range of separating density, etc. The main principle is that the feedstock stratifies by bed density, with the lighter particles (clean coal) floating and the denser particles (tailings) sinking based on the Archimedes theorem. Thus, the crucial solution is to maintain stable fluidization and form uniform density distribution in the bed by selecting suitable fluidized media and seeking optimal operating parameters for the effective separation of coal. A number of researchers in many countries have contributed to the development of gas-solid fluidized bed beneficiation technology (Dwari and Rao, 2007, Sahu et al., 2009; Mohanta et al., 2013). Gupta et al. (2013) utilized an air dense-medium fluidized bed (ADMFB) to separate low-ash lignite. They were able to obtain a clean coal recovery of 95.6% with an ash content of 10.6% and separation efficiency of 15.29% with the optimum operating condition. Sahu et al. (2011, 2013) reported a few favorable achievements when separating high-ash Indian coal by an air dense-medium fluidized bed separator. They proposed a novel method to evaluate the stability of particulate fluidization system by applying fluidization index (Singh and Roy, 2005). Firdaus et al. (2012) beneficiated different size fractions of coarse coal (5–31 mm) using an air fluidized bed dry dense-medium separator with silica/zircon sands as the fluidizing medium and obtained satisfactory separation results. Oshitani et al. (2013) utilized gas-solid fluidized bed separator to effectively separate particulate iron ore (250-500 μm) based on the density-segregation. Researchers at the China University of Mining and Technology (CUMT) have contributed to the development of dry coal beneficiation technique using a dense-medium gas-solid fluidized bed since 1980s, and have achieved a series of theoretical and application results (Chen and Wei, 2005; Luo and Chen, 2001; Zhao and Wei, 2000). The effective separation of 6–50 mm run-of-mine (ROM) coal has been realized on a semi-industrial scale. Furthermore, in order to solve the separation difficulty of < 3 mm fine coal, some new separation techniques have therefore been proposed by introducing vibrational or magnetic energy into conventional fluidized bed separator which are named as vibrated fluidized bed (VFB) and magnetic fluidized bed (MFB) (Luo et al., 2008; Fan et al., 2002). Particularly, the separation efficiency of 1-3 mm fine coal can be improved significantly by the VFB under suitable operating conditions (He et al., 2015a; He et al., 2015b). Triboelectrostatic separation technology has been proposed to deal with <1 mm fine coal by the differences of electrical property of coal and gangue particles (Tao et al., 2015).

In the investigation, the mixing mechanism of 0.15–0.3 mm coarse Geldart B magnetite powder and <0.15 mm fine magnetite powder was studied to seek the optimal proportioning of fluidized media. The segregation of 3–13 mm high-ash coal was investigated using various operating factors of static bed height and superficial gas velocity. When treating the coal with a laboratory-scale fluidized bed separator, the separation efficiency and product quality at each condition were assessed.

Experimental

Experimental apparatus

The schematic diagram of experimental system is illustrated in Fig. 1. It mainly consisted of an air supply, a flow controlling device, a fluidized bed, an air distributor, measurement devices for parameters, a dust collector, etc.

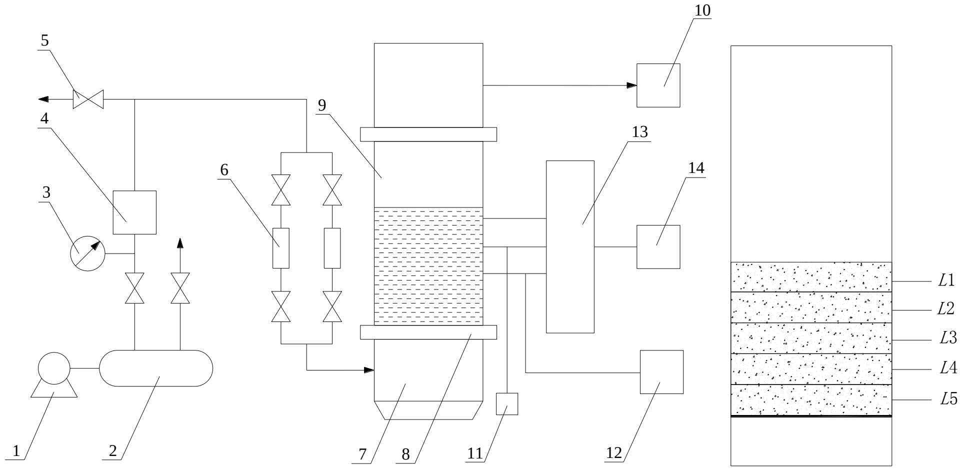

Fig. 1. Schematic diagram of the experimental system with a fluidized bed: 1 – Air blower, 2 – Air buffer, 3 – Pressure meter, 4 – Filter, 5 – Valve, 6 – Flowmeter, 7 – Air chamber, 8 – Air distributor, 9 – Fluidized bed, 10 – Dust collector, 11 – Pressure sensor, 12 – Differential pressure densimeter, 13 – Pressure transmitter, 14 – Recorder

The compressed air generated by the air blower was transferred into the air chamber below the fluidized bed which acted as the air distributor. The gas flow was controlled by a valve and observed using a flowmeter. The air distributor was designed and made based on the uniform air distribution theory of the gas-solid fluidized bed (Luo et al., 2004; Luo and Zhao, 2002). It was made up of a micro-perforated plate with the double-layer filter cloth covering both sides of the plate, which ensured uniform distribution of the fluidized gas when entering into the bed. With the suitable fluidized media and operating gas velocity, stable fluidization with the steady fluctuation of bed pressure drop and uniform bed density distribution were achieved in the fluidized bed. The bed pressure drop and density were measured by the pressure sensor and differential pressure densimeter, respectively. Fine particles and dust that escaped from the bed top were collected by a dust collector.

Evaluation indicators

The stabilities of bed density and particle-size distribution are two important indicators to determine the separation performance of coal. Thus, the standard deviations of bed densities and particle-size distributions at various layers, S_ρ and S_d, are proposed to characterize the stabilities of bed density and particle-size distribution across the interspaces of the bed, and are defined by Eqs 1 and 2:

$$S_\rho = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\rho_i - \bar{\rho})^2} \tag{1}$$

$$S_d = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(w_i - \bar{w})^2} \tag{2}$$

where ρ_i is the instantaneous density value in location i , g/cm^3; $\bar{\rho}$ is mean density, g/cm^3; n is the number of measurement points in bed; w_i is weight fraction of different particle-sized material in layer *I*, %; $\bar{w}$ is mean weight fraction of certain particle-sized material in all layers, %.

In the segregation experiments, the separating medium solids were fluidized by the uniform gas initially. After achieving stable fluidization, the coal samples were fed into the bed and separated for a certain period. Then, the gas supply was shut down and the bed fell down immediately to be static. Finally, the whole bed was divided into five layers (*L*1–*L*5) along the axial direction of the bed. *L*1–*L*5 represents the top layer to the bottom layer, respectively, as illustrated in Fig. 1. The coal sample of each layer was sieved out and collected to measure its mass fraction and ash content. In order to evaluate the segregation performance of coal sample, segregation degree S_ash was proposed in the study, as defined by Eq.(3)

$$S_{ash} = \sum_{j=1}^{N}\left[\gamma_j \cdot \left|\frac{A_j}{A_0} - 1\right|\right] \tag{3}$$

where A_0 is the initial ash content of feeding coal, %; A_j is ash content of coal sample in layer *j*, %; γ_j is mass fraction of coal sample in layer *j*, %; *N* is the total number of layers.

Results and discussion

Characteristics of separating media and coal sample

Magnetite powder has been considered as a fluidized medium for coal beneficiation. Its main component was Fe_3O_4, and a small amount of Fe_2O_3 and SiO_2. It showed favorable characteristics of steady property, uniform density and easy recycling. The weight fractions and physical properties for the various sizes of magnetite powder are shown in Table 1. The dominant size fractions were 0.15–0.3 and 0.074–0.15 mm, which accounted for 85.34% of the whole. The true density of the magnetite powder was 4.5 g/cm^3. The bulk density decreased gradually from 2.85 to 2.41 g/cm^3 with the decrease in size fraction. This was because the voids between the magnetite particles gradually increased with decreasing size. The magnetite content was higher than 98.20% in all cases, indicating a strong magnetism. The overall properties of the magnetite powder indicate a uniform composition of size fraction, a stable density distribution and a higher magnetic content, which indicated that magnetite powder can be utilized as a basic separating media for coal beneficiation.

Table 1. Weight fractions and physical properties for the various sizes of magnetite powder

Size fraction (mm)	Weight fraction (%)	Cumulative oversize fraction (%)	Cumulative undersize fraction (%)	Bulk density (g/cm^3)	Magnetic content (%)
0.3-0.5	6.75	6.75	100.00	2.85	98.35
0.15-0.3	71.72	78.47	93.25	2.79	98.76
0.074-0.15	13.62	92.09	21.53	2.62	99.28
0.045-0.074	4.02	96.11	7.91	2.53	99.43
<0.045	3.89	100.00	3.89	2.41	99.51
Total	100.00				

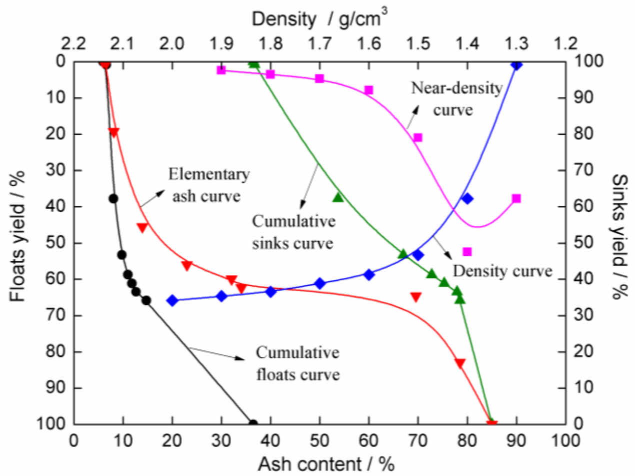

Fig. 2. Washability curves of ROM coal sample

Proximate analysis of the run-of-mine (ROM) coal sample from JiNin mining area (China) indicated a low moisture content of 2.39%, high ash content of 35.58%, volatile matter content of 17.22%, low sulfur content of 0.95%, and high calorific value of 31.46 MJ/kg. Washability of the ROM coal was analyzed by the float-sink tests, as summarized in Table 2 and in Fig. 2. The dominant density fractions were 1.3-1.4 and 1.4-1.5 g/cm^3 with a mean ash content of 9.81%, and >2.0 g/cm^3 with an ash content of 78.49%, accounting for 86.60% of the total material. It indicated that the sufficient dissociation of high-density and low-density materials was achieved in ROM coal, which was greatly beneficial to the effective separation of coal. The theoretical yield of clean coal would be more than 60% with an ash content of 11.0% at a separating density of 1.65 g/cm^3. Therefore, the near-density material content of 12.1% was obtained, which indicated that the ROM coal belonged to a moderate-to-separate coal.

Table 2. Float-sink results of 3–13 mm coarse coal sample

Density (g/cm^3)	Weight (%)	Ash content (%)	Floats		Sinks		Separating density δ±0.1	
			Weight (%)	Ash content (%)	Weight (%)	Ash content (%)	Density (g/cm^3)	Weight (%)
<1.3	0.83	6.57	0.83	6.57	100.00	35.58	1.30	37.76
1.3–1.4	36.93	8.10	37.76	8.07	99.17	35.82	1.40	52.46
1.4–1.5	15.53	13.89	53.29	9.77	62.24	51.83	1.50	20.98
1.5–1.6	5.45	22.98	58.74	10.99	46.71	65.04	1.60	8.05
1.6–1.8	4.72	32.05	63.46	12.56	41.26	70.59	1.70	4.39
1.8–2.0	2.40	34.05	65.86	13.34	36.54	75.57	1.90	2.40
>2.0	34.14	78.49	100.00	35.58	34.14	78.49		
Total	100.00	35.58						

Fluidization stability and density uniformity of fluidized bed

Previous results indicated that excessively coarse magnetite powder (>0.3 mm) was not suitable for coal separation as the separating media (Luo and Zhao, 2002). The accumulation of excessively coarse magnetite powders observably increases the resistance of the fluidized bed, which needs a larger minimum gas velocity to fluidize the bed. Thus, more energy input and consumption is required under this condition. In addition, large void space of coarse magnetite powder bed results in the formation of larger-sized bubbles, which decreases the fluidization stability and the density uniformity of the bed. Therefore, the coarse magnetite powder of 0.3–0.5 mm was not used as the fluidized media in the study. As a result, magnetite powder with various size fractions of 0.15–0.3, 0.074–0.15, 0.045–0.074 and <0.045 mm were used to perform the fluidization tests, respectively.

The variation of pressure drop of the whole bed with superficial gas velocity for various magnetite size fractions is shown in Fig. 3. The fluidization results indicated that the initially the fluidized gas velocity of the bed increased with the increase in size fraction of magnetite powder. The fluidization of the bed was relatively stable for the 0.15–0.3 and 0.074–0.15 mm magnetite size fractions. Fluidization stability of the bed was significantly favorable with slight fluctuations of bed pressure drops. However, the fluidization quality sharply worsened with the size fraction of magnetite powder below 0.074 mm, especially for <0.045 mm magnetite powder, which had intense fluctuation of bed pressure drop. The bed became an aggregative bubbling fluidized bed in this case. The reason was that the surface area of the fine particles was larger than that of coarse particles, so the surface adhesion between the fine particles was very strong, even leading to particle agglomeration. Thus, the fluidization behavior of fine-particle bed was poor, leading to "dead regions" or "plug flow" in some parts of the bed. It had negative effects on stable fluidization, which greatly weakened the stability of the whole bed.

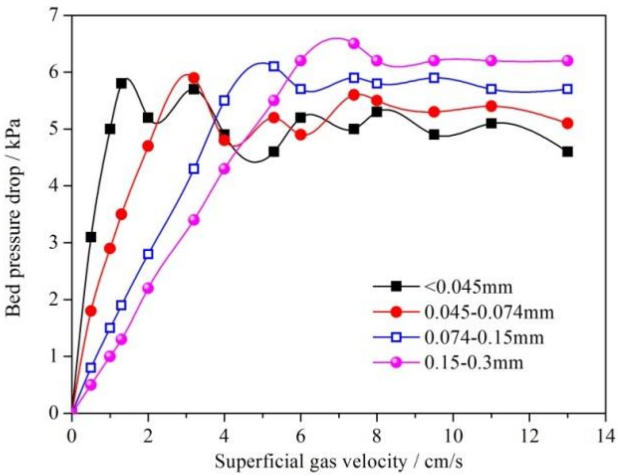

Fig. 3. Variation of bed pressure drop of the whole bed for various magnetite size fractions

The results revealed that the optimal size fraction of magnetite powder is 0.15–0.3 mm to achieve stable fluidization. However, in order to reduce the preparation cost and increase the yield of the narrow-sized magnetite powder, it was allowed to mix a small amount of <0.15 mm magnetite powder into the fluidized media. Furthermore, the large volumes of 0.15–0.3 mm coarse magnetite powder increased the void space of the bed. When adding a certain amount of <0.15 mm magnetite powder, fine powders can fill the gaps between coarse powders, broaden the particle size distribution in the bed, and reduce the mean particle size of the mixed fluidized media. Thus, the bed was easily fluidized because of the strong surface-adhesion strength of fine powders, which resulted in an increase in the buoyancy and drag force that acted on the bed layer. Therefore, adding a certain amount of fine powders into the coarse magnetite powder helped to enhance the fluidity and activity of the bed as well.

Various proportions of <0.15 mm magnetite powder were mixed into the 0.15–0.3 mm magnetite powder as fluidized media to determine the desired mixing proportion by the fluidization tests. After achieving complete fluidization, the densities at various bed layers (*L*1 to *L*5) were measured from bed top to bottom. Then, three size fractions of magnetite powder (0.074–0.15, 0.045–0.074 and <0.045 mm) were collected by screening the material of each layer after fluidization. The weight distributions of three size fractions at each layer were measured and the evolution indicators S_ρ and S_d were used to determine the stability and uniformity of the bed.

Figure 4 presents the variation of the particle-size distribution and density distribution in the bed with increasing weight fraction of <0.15 mm magnetite powder ($w_{<0.15}$) in the fluidized media. When $w_{<0.15}$ ≤15% (weight fraction, %), the standard deviations of particle-size distributions S_d values were all less than 2.5%. Smaller S_d values indicated that there was no obvious stratification for variously sized magnetite powder. When 15% <$w_{<0.15}$≤25%, S_d value of <0.045 mm magnetite powder increased from 2.31% to 6.33%, and an obvious stratification occurred for <0.045 mm powder. Similarly, when 25% < $w_{<0.15}$ ≤ 35%, S_d value of 0.074–0.15 mm magnetite powder increased from 0.15% to 2.02%, without a sharp increasing, no obvious stratification occurred for 0.074–0.15 mm powder as well. However, when $w_{<0.15}$ > 35%, S_d values of all three different sized magnetite powder increased sharply, which clearly suggested that each size fraction of magnetite powder showed obvious stratification in the bed. The standard deviation of density distribution (S_ρ value) also increased sharply from 0.015 to 0.09 g/cm^3. Redundant weight fraction of <0.15 mm magnetite powder in the fluidized media worsened the fluidization stability of the bed and brought intense density fluctuation. Thus, the bed stability was significantly influenced by the weight fraction of <0.15 mm magnetite powder in the fluidized media. Normally $w_{<0.15}$ should not exceed 35% for coal separation. In this study, a suitable value for $w_{<0.15}$ was approximately 21.53%.

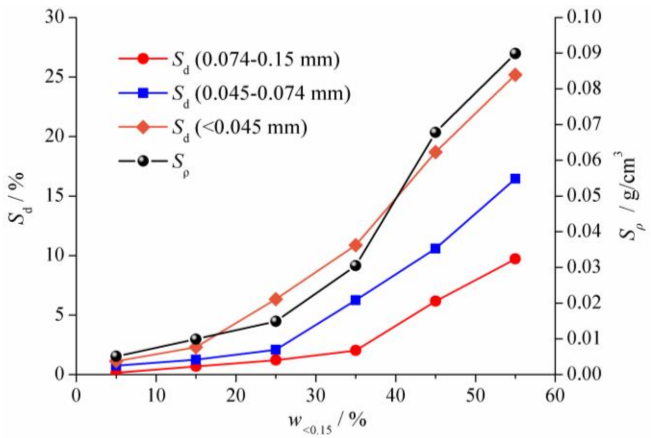

Fig. 4. Particle-size and density distributions with various contents of <0.15 mm magnetite powder

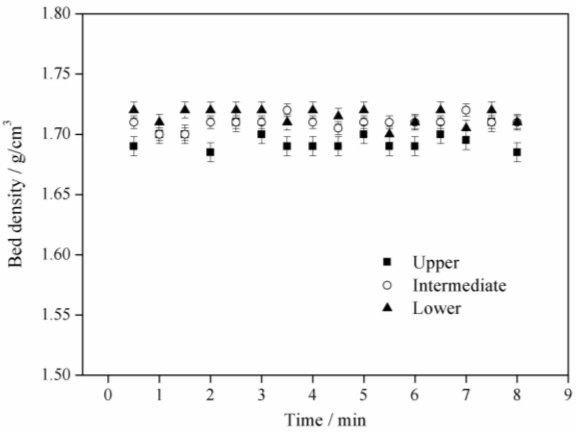

Fig. 5. Distribution of bed densities after stable fluidization within 8 minutes

When the bed achieved stable fluidization, the bed densities for three layers were measured for 8 minutes with a time scale of 30 seconds, as shown in Fig. 5. The densities of the lower and intermediate layers of the bed were more uniform with smaller fluctuation compared to the upper layer. The mean densities were 1.728 and 1.716 g/cm^3 with S_ρ values of 0.018 and 0.023 g/cm^3 for the lower and intermediate layers, respectively. The mean density of the upper layer was 1.705 g/cm^3 with a S_ρ value of 0.035 g/cm^3. This can be explained by the bubbling behavior and the circulating and remixing of fine particles at the top layer of the bed. Most rising bubbles split and escaped from the bed top, resulting in an unstable state in the upper interspaces. Fine particles attached by the rising bubbles tended to rise and gather in the upper layer of the bed. This leaded to a lower mean bed density with a larger fluctuation.

Segregation and separation performance of 3–13 mm coarse coal

Dry separation was effectively realized based on “segregation” of the coal particles in a fluidized bed. When a mixture of coal particles was fed into a fluidized bed, heavier particles moved down and lighter particles moved up in the bed. Normally the feeding coal particles were separated to the clean coal (floats) and tailings (sinks) by bed density, which was called “density-segregation”.

Static bed height H_s and superficial gas velocity U are two critical factors to determine the segregation/separation performance of coal particles in a fluidized bed. Thus, the segregation efficiency (S_{ash} value) was used to determine the optimal values of H_s and U. Figure 6 illustrates the segregation results of different coal size fractions for various static bed heights. S_{ash} values gradually increased with increasing H_s from 30 to 80 mm and reached a peak value at H_s = 80 mm. The S_{ash} values then suddenly decreased with increasing H_s from 80 to 150 mm. This was because that at lower bed heights, sufficient space was not available for the segregation of coal particles. Thus, the density-based stratification of denser and lighter particles was greatly affected by the limited movement distance along the vertical direction of the bed. In contrary, at greater bed heights, the rising distance of bubbles increased, which weakened the activity of bubbles and consumed more energy in the rising. This also enhanced the back-mixing and aggregation of fine magnetite powders due to the increase of circulation space in the bed for the fine particles, which negatively affected the segregation performance of coal particles. Consequently, coal particles at various bed layers remixed and gathered again, which had previously achieved a favorable segregation. Thus, the static bed height H_s should be maintained in the range of 70-90 mm. In this case, the S_{ash} values generally exceeded 0.63, 0.70 and 0.72 for 3-6, 6-10 and 10-13 mm coal fractions, respectively. In particular, the S_{ash} reached peak values of 0.67, 0.73 and 0.76 for the above three size fractions at H_s =80 mm.

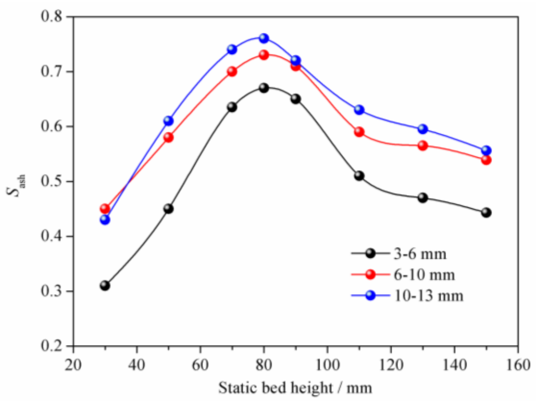

Fig. 6. Segregation results of different coal size fractions for various static bed heights

The fluidization number U^* ($U^* = U/U_{mf}$, U_{mf} refers to minimum fluidization velocity) was used to validate the effects of superficial gas velocity on the segregation efficiency. The value of U_{mf} was 7.4 cm/s, which was determined by previous fundamental fluidization experiments (He et al., 2012). The segregation results of different coal size fractions at various superficial gas velocities are shown in Fig. 7. The S_{ash} values increased rapidly with increasing U^* from 1.1 to 1.6, indicating that the segregation efficiency was greatly improved by increasing gas velocity. When U^* = 1.6, maximum S_{ash} values of 0.67, 0.74, and 0.76 were obtained for 3–6, 6–10 and 10–13 mm coal fractions, respectively. When $U^* > 1.6$, S_{ash} values decreased sharply with the increasing of U^*. This indicated that coal particles at different bed layers changed to a mixing state, worsening segregation performance. The reason for this is that a sufficient fluidization state was not achieved at a lower superficial gas velocity ($U^* <$ 1.5). Therefore, the bed was relatively steady with only a small amount of bubbles passing through the bed. The packed fine magnetite powders could not be completely fluidized, resulting in poor segregation performance. When the gas velocity exceeded a certain value ($U^* > 1.7$), the stable fluidization state was gradually destroyed with a number of large-sized bubbles moving through the bed, which weakened the fluidization stability of the bed and enhanced the remixing and aggregation of fine powders. Thus, the bed density became uneven because of the intensive and confused interaction between the bubbles and media particles. Therefore, U^* should be adjusted in the range of $1.5 \leq U^* \leq 1.7$ to ensure the favorable segregation of coal particles. In this case, S_{ash} values were greater than or equal to 0.62, 0.70 and 0.72 for the above three coal size fractions, respectively.

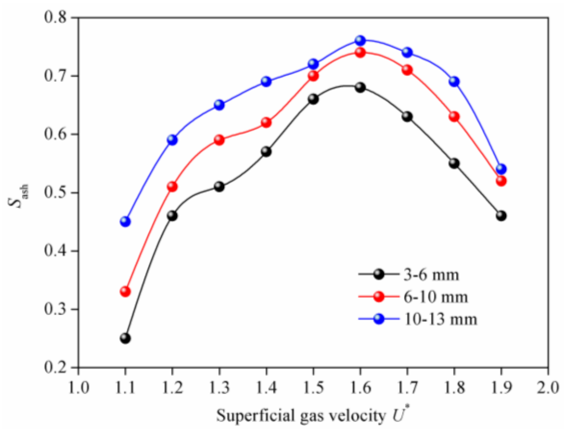

Fig. 7. Segregation results of different coal size fractions
at various superficial gas velocities

Additionally, S_{ash} values of various sized coal particles decreased with a decrease in the coal particle size. This indicated that the smaller the coal particle size, the lower the segregation efficiency. Thus, the separation difficulty of coal greatly increased for smaller-sized coal based on its density-segregation. This was because the particle-size differences between the feeding coal and fluidized media should be as large as possible to avoid the hindered falling between coarse coal particles and magnetite powders (Tripathy et al., 2015). Thus, the segregation efficiency of 3–6 mm coal was a little lower than that of 6–10 and 10–13 mm coal because its particle size was much closer to the fluidized media. However, the overall density–segregation performance of 3–13 mm coarse coal satisfy the requirements of further separation with a laboratory–scale fluidized bed separator.

The separation experiments of 3–13 mm coal were performed with a laboratory–scale fluidized bed separator. After achieving stable fluidization, a certain amount of 3–6, 6–10 and 10–13 mm coal samples were fed into the separator, respectively. After a separating time of 90 seconds, the feedstock stratifies by the density differences. Then, the clean coal, middlings, and gangue were discharged from the bed to perform a float-sink experiment.

Figure 8 presents the partition curves of the separation experiments for three coal size fractions. The partition coefficient represents the mass fraction of the coal particles reporting to the tailing. The coal particles with the densities of ρ_{25}, ρ_{50} and ρ_{75} have the mass fractions of 25%, 50% and 75%, respectively. ρ_{50} represents the separating density in the experiment. The value of probable error E was calculated as $(\rho_{75}–\rho_{25})/2$. A lower E value indicates a better separation performance.

The separation results of various sized coal samples are summarized in Table 3. The ash contents of 3–6, 6–10 and 10–13 mm coal were reduced from 36.48% to 12.47%, 11.57% and 10.90% at the separating densities of 1.62, 1.71 and 1.80 g/cm^3, respectively. The low-ash clean coal with the yields of 50.79, 56.83, and 61.24% were acquired, and high-ash gangue with the yields of 38.94, 34.33, and 32.27% were discharged for the coal samples of various size fractions. The probable error E values were 0.07, 0.055 and 0.05 g/cm^3 for 3–6, 6–10 and 10–13 mm coal, respectively, which indicated that the separation efficiency of various sized coal gradually decreased with the decrease of coal size fraction. Required separating density increased with increasing coal size fraction, which depended on the density compositions of different coal size fractions. Altogether the effective separation of 3–13 mm coarse coal was achieved and its quality was greatly improved by the dry beneficiation and cleaning technology of dense-medium gas-solid fluidized bed.

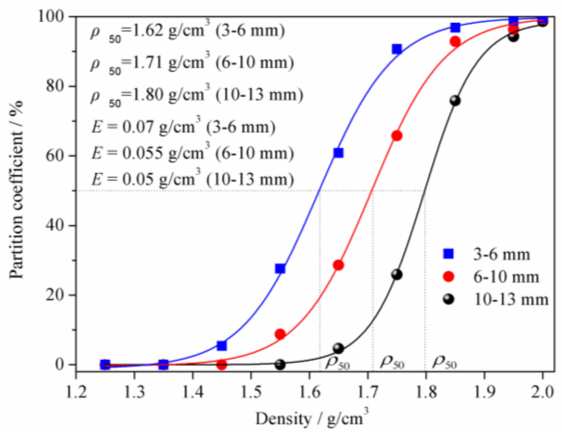

Fig. 8. Partition curves of the continuous separation experiments

Table 3. Separation results of the coal samples of various size fractions

Size fraction (mm)	Clean coal		Middlings		Gangue		Separating density (g/cm^3)	E (g/cm^3)
	Yield (%)	Ash content (%)	Yield (%)	Ash content (%)	Yield (%)	Ash content (%)		
3-6	50.79	12.47	10.27	31.71	38.94	66.69	1.62	0.07
6-10	56.83	11.57	8.84	30.43	34.33	69.31	1.71	0.055
10-13	61.24	10.90	6.49	35.01	32.27	71.41	1.80	0.05

Conclusions

Magnetite powder primarily in the size range of 0.15–0.3 mm with 21.53 % fines of <0.15 mm was utilized as the basic separating media in a dry fluidized bed. Fine magnetite powder enhanced the fluidity and activity of the bed. Using the material, uniform density distribution with the mean bed densities of 1.728 and 1.716 g/cm^3 and S_ρ values of 0.018 and 0.023 g/cm^3 for the lower and intermediate layers in the bed were obtained, which was beneficial for dry coal separation.

Density-segregation of 3-13 mm coal occurred under suitable operating conditions. The peak S_{ash} values of 0.67, 0.73 and 0.76 were achieved with a static bed height H_s of 80 mm for 3–6, 6–10 and 10–13 mm coal, respectively. Similarly, the S_{ash} values reached a maximum of 0.67, 0.74 and 0.76 for a superficial gas velocity of $1.6U_{\text{mf}}$ (11.84 cm/s) for the same three coal size fractions. Using these conditions, the low-ash clean coal with yields of 50.79, 56.83, and 61.24% were obtained by a laboratory-scale fluidized bed separator for the same three coal size fractions, respectively. Corresponding probable error values were 0.07, 0.055, and 0.05 g/cm^3, indicating an efficient separation. Dry coal beneficiation technique using dense-medium fluidized bed separation for coal cleaning would be beneficial in arid and water-shortage regions.

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References

AZIMI E., KARIMIPOU S., RAHMAN M., SZYMANSKI J., GUPTA R., 2013. *Evaluation of the performance of air dense medium fluidized bed (ADMFB) for low-ash coal beneficiation, Part 1: Effect of operating conditions*. Energy & Fuels, 27, 5595-5606.

CHEN Q.R., WEI L. B., 2005. *Development of coal dry beneficiation with air-dense medium fluidized bed in China*. China Particuology, 3, 42.

DWARI R. K., RAO K. H., 2007. *Dry beneficiation of coal-A review.* Mineral Processing and Extractive Metallurgy Review, 28, 177-234.

FAN M. M., CHEN Q. R., ZHAO Y. M., GUAN Y. P., LI B., 2002. *Magnetically stabilized fluidized beds for fine coal separation*. Powder Technology, 123, 208-211.

FIRDAUS M., O'SHEA J. P., OSHITANI J., FRANKS G. V., 2012. *Beneficiation of coarse coal ore in an air-fluidized bed dry dense-medium separator*. International Journal of Coal Preparation and Utilization, 32, 276-289.

HE J.F., ZHAO Y.M., LUO Z.F., ZHAO J., DUAN C. L., HE Y. Q., 2015a. *Improving the separation efficiency of 6-1mm fine coal by introducing vibration energy to dense medium gas-solid fluidized bed*. Physicochemical Problems of Mineral Processing, 51, 95-108.

HE J.F., ZHAO Y.M., ZHAO J., LUO Z.F., DUAN C. L., HE Y. Q., 2015b. *Enhancing fluidization stability and improving separation performance of fine lignite with vibrated gas-solid fluidized bed*. Canadian Journal of Chemical Engineering, 93, 1793-1801.

HE J.F., 2012. *Numerical simulation of multiphase fluid dynamic in air dense medium fluidized bed based on Euler-Euler model*. PhD Thesis: China University of Mining and Technology, Xuzhou, China.

LUO Z. F., CHEN Q. R., 2001. *Dry beneficiation technology of coal with an air dense-medium fluidized bed*. International Journal of Mineral Processing, 63, 167-175.

LUO Z. F., FAN M. M., ZHAO Y. M., TAO X. X., CHEN Q. R., CHEN Z. Q., 2008. *Density-dependent separation of dry fine coal in a vibrated fluidized bed*. Powder Technology, 187, 119-123.

LUO Z. F., ZHAO Y. M., 2002. *Separation Theory of Fluidization*. China University of Mining and Technology Press, Xuzhou, China.

MOHANTA S., RAO C. S., DARAM A. B., CHAKRABORTY S., MEIKAP B.C., 2013. *Air dense medium fluidized bed for dry beneficiation of coal: Technological challenges for future. Particulate Science and Technology, 31, 16-27.*

OSHITANI J., OHNISHI M., YOSHIDA M., FRANKS G. V., KUBO Y., NAKATSUKASA S., 2013. *Dry separation of particulate iron ore using density-segregation in a gas-solid fluidized bed*. Advanced Powder Technology, 24, 554-559.

SAHU A.K., BISWAL S. K., PARIDA A., 2009. *Development of air dense medium fluidized bed technology for dry beneficiation of coal-A review.* International Journal of Coal Preparation and Utilization, 29, 216-241.

SAHU A.K., TRIPATHY A., BISWAL S.K., PARIDA A., 2011. *Stability study of an air dense medium fluidized bed separator for beneficiation of high-ash Indian coal*. International Journal of Coal Preparation and Utilization, 31, 127-148.

SAHU A.K., TRIPATHY A., BISWAL S.K., 2013. *Study on particle dynamics in different cross sectional shapes of air dense medium fluidized bed separator*. Fuel, 111, 472-477.

SINGH R. K., ROY G. K., 2005. *Prediction of minimum bubbling velocity, fluidization index and range of particulate fluidization for gas-solid fluidization in cylindrical and non-cylindrical beds.* Powder Technology, 159, 168-172.

TAO Y. J., DING Q. Q., DENG M. R., TAO D. P., WANG X., ZHANG J., 2015. *Electrical properties of fly ash and its decarbonization by electrostatic separation*. International Journal of Mining Science and Technology, 25, 629-633.

TRIPATHY S.K., BHOJA S. K., KUMAR C. R., SURESH N., 2015. *A short review on hydraulic classification and its development in mineral industry*. Powder Technology, *270,* 205-220.

ZHAO Y.M., LIU J.T., Wei X.Y., LUO Z.F., CHEN Q.R., SONG S.L., 2011. *New progress in the processing and efficient utilization of coal.* Mining Science and Technology (China), 21, 547-552.

ZHAO Y. M., WEI L. B., 2000. *Rheology of gas-solid fluidized bed*. Fuel Processing Technology, 68, 153-160.