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IMPROVING SEPARATION EFFICIENCY OF 6-1 MM COAL BY INTRODUCING VIBRATION ENERGY TO DENSE MEDIUM GAS-SOLID FLUIDIZED BED

Jingfeng HE, Yuemin ZHAO, Zhenfu LUO, Jie ZHAO, Chenlong DUAN, Yaqun HE

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

Abstract: Effects of the vibration energy on the fluidization quality and separation performance of dense medium gas-solid fluidized bed were investigated experimentally. The magnetite powder with a wide size range of 0.3-0.074 mm was utilized as the basic medium solids. 6-1 mm fine coal sample from Yongcheng (China) was used to perform the separation experiments. The results indicate that the vibration amplitude A and superficial gas velocity U are greatly significant to the fluidization stability and the density distribution uniformity. Comparing with the bed without vibration, the optimal S_P and S_ρ values of 0.034 kPa and 0.018 g/cm^3 are acquired in vibration bed with the operating factors of A = 1 mm, $U = 1.8U_{\mathrm{mf}}$, f = 15 Hz and H_s = 150 mm. The coal ash content was reduced from 27.84% to 9.50% at a separating density of 1.68 g/cm^3 with a probable error E value of 0.505. The separation efficiency of 6-1mm fine coal is effectively improved by introducing vibration energy to dense medium gas-solid fluidized bed. The technology provides a novel approach to achieve high-efficiency separation of 6-1 mm fine coal in the arid and water-shortage areas.

Keywords: *vibration energy, dense medium gas-solid fluidized bed, fluidization quality, density uniformity, separation efficiency*

Introduction

The high-efficiency coal beneficiation has been recognized as the most efficient approach to achieve the coal resource saving and environment protection. Water-based wet separation technology is the traditional coal beneficiation process, which has been widely popularized around the world, including the wet dense medium cyclone separation, hydraulic jigging separation, flotation etc. (Brozek and Mlynarczykowska, 2013; Nakhaei and Irannajad, 2013; Svoboda et al., 1998; Sampaio et al., 2008; Zou et al., 2013). However, these technologies are not suitable for the coal separation in arid

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and water-shortage areas and countries. Especially, as the gradually decreasing of coal resource, the exploitation and utilization of low-rank coal has become the focused concern. Brown coal is a type of the common low-rank coal, which shows the special physical property of an easy degradation in water. Thus, it is unfavorable to separate brown coal by wet processing technology as well. Therefore, it is significantly important to develop a dry coal beneficiation technology in current energy utilization field.

Recently, a number of scientists and engineers in many countries have contributed to the dry coal beneficiation technology based on the dense medium gas-solid fluidized bed (DMGFB). With the fine glass beads of 2500 kg/m^3 as basic separating medium, Takana and Sato (1996) utilized a 0.2 m × 0.1 m rectangular fluidized bed separator to separate the mixed coal sample with the densities of 1300 and 1700 kg/m^3. The coal ash content was reduced from 8.50% to 3.50%. Sahu et al. (2011) investigated the stability of an air dense medium fluidized bed separator (ADMFBS) by different expressions. Indian high ash noncoking coal at particular size (-25+6 mm) was separated with the pilot-scale ADMFBS. The probable error *E* and imperfection value were found to be 0.12 and 0.071, respectively. Macpherson et al. (2010) designed a Reflux Classifier with an air-sand dense-medium and vibration to achieve an effective separation of 1–8 mm fine coal. Xu et al. (2010) studied the separation performance of bituminous coal by a laboratory continuous Air Dense Medium Fluidized Bed separator. The coal ash content was reduced from 26% to 10% with a recovery rate of 80% for the cleaning coal. Technology University of Aachen developed a new type of vibrating fluidized bed separator without utilizing the separating medium. Raw coal sample with an ash content of 47.5% was effectively separated, and the cleaning coal and tailings with ash contents of 9.6% and 40.0% were finally obtained (Weitkamper et al., 2010). China University of Mining and Technology have been contributing to the fundamental theoretical research and practical application of DMGFB for dry coal beneficiation since 1980s, acquiring lots of achievements in the past few years (Chen and Yang, 2003; Zhao et al., 2004, 2012; He et al., 2012, 2013a-c, 2014). The technology could form stable dense medium fluidized bed by utilizing the fluidizing gas and medium solids within a specified size range. According to Archimedes theorem, the feedstock stratifies according to the bed density with the lighter particles (cleaning coal) floating and the denser particles (tailings) sinking. At present, the 40-60 Mg/h pilot dry coal beneficiation system based on DMGFB has been established and developed, which could achieve a highly efficient separation of 50–6 mm raw coal. However, as the development of the large-scale mechanized coal mining, the cumulative production of <6 mm fine coal increase rapidly year by year. Thus, it is of great significance to develop a novel fine coal beneficiation technology. Normally, the magnetite powder with a wide particle size distribution of 0.3–0.074 mm is utilized as the basic separating medium solids for different sized raw coal. Comparing with the beneficiation of 50–6 mm coarser coal, it needs finer separating medium solids to achieve the effective separation of <6 mm fine coal. The increasing of the specific surface area of fine magnetite powder leads to the increase of viscosity between medium solids and the decrease of their kinetic activities. The fluidization quality of the bed becomes worsen with unstable bubble dynamical behaviors and circulating back-mixing of fine coal and medium solids, resulting in a bad and unsteady separation performance of <6mm fine coal by density differences. Hence, the vibration and magnetic energy were introduced to fluidized bed in order to improve the separation efficiency (Luo and Chen, 2001; Luo et al., 2002, 2008; Luo and Zhao, 2002). The vibration energy cross the bed could suppress the generation of large bubbles and strengthen the contacting of gas-solid phases and solid-solid phases. The fluidization quality could be significantly improved.

In this work, the fluidization characteristics and separation performance of the DMGFB with and without the vibration were investigated and compared. The significance of the critical operating factors acting on the fluidization quality was analyzed. The separation experiments of 6-1 mm fine coal sample were carried out by applying the fluidized bed separator with and without the vibration, respectively. The improvement of separation efficiency by introducing the vibration energy to DMGFB was studied.

Material and Methods

Materials

Separating medium solids

Preparation of fine magnetite powder needs more energy consumption in the sieving and grinding process. Additionally, it also brings great difficulty for the recycling and reutilization of fine magnetite powder. Thus, it is not suitable for industrial application to use the fine magnetite powder as the separating medium. Therefore, the magnetite powder with a wide particle size distribution of 0.3–0.074 mm was utilized along in the study. The physical properties of different sized magnetite powder are shown in Table 1. The size fractions of the magnetite powder are divided into nine grades. The test results show that the dominant size fractions are 0.3–0.2, 0.2–0.15, 0.15–0.125, 0.125–0.1 and 0.1–0.074 mm, which accounts for 92.55% of the whole. The real density is 4.2 g/cm^3. The bulk density decreases gradually from 2.88 to 2.42 g/cm^3 with the decrease in fraction size. It is because that the interspaces between the magnetite powders increase gradually with the size decrease. The magnetic material content and magnetization are all larger than 99.30% and 76.0 A^2/kg, respectively. The overall physical properties of the magnetite powders indicate a uniform composition of size fraction, a stable density distribution and a higher magnetic material content. Thus, it is greatly favorable to form the steady fluidization environment and uniform density distribution for coal beneficiation by density.

Table 1. The physical properties of magnetite powder

Size fraction (mm)	Yield (%)	Real density (g/m^3)	Bulk density (g/cm^3)	Magnetic material content (%)	Magnetization (A^2/kg)
>0.300	1.10	4.2	2.88	99.36	76.01
0.300-0.200	20.91	4.2	2.85	99.53	76.21
0.200-0.150	28.39	4.2	2.71	99.61	77.33
0.150-0.125	20.33	4.2	2.66	99.59	77.52
0.125-0.100	17.46	4.2	2.62	99.72	77.98
0.100-0.074	5.36	4.2	2.59	99.68	78.11
0.074-0.060	2.51	4.2	2.55	99.43	78.16
0.060-0.050	3.02	4.2	2.52	99.52	78.21
<0.050	0.82	4.2	2.42	99.79	78.76

Raw coal sample

The basic properties of 6-1mm fine coal sample from Yongcheng (China) were analyzed. The sample has a low moisture content of 2.68%, an ash content of 27.84%, a volatile component of 9.22%, a low sulphur content of 0.37%, and a high heat productivity of 30.51 MJ/kg.

The washability of fine coal sample was analyzed by the float-sink tests, as shown in Table 2 and Fig. 1. The dominant density distribution are <1.3, 1.3-1.4, 1.4-1.5 g/cm^3 with a mean ash content of 8.66% and >2.0 g/cm^3 with an ash content of 86.41%, accounting for 90.22% of the total products. It indicates that a sufficient dissociation of low-density and high-density products is achieved in fine coal sample, which is beneficial to achieve effective separation.

Table 2. The float-sink results of 6-1mm fine coal sample

Density (g/cm^3)	Yield (%)	Ash content (%)	Accumulation				Separating density δ±0.1	
			Floats		Sinks			
			Yield (%)	Ash content (%)	Yield (%)	Ash content (%)	Density (g/cm^3)	Recovery (%)
<1.3	9.62	4.68	9.62	4.68	100.00	27.72	1.30	55.22
1.3-1.4	45.60	7.67	55.22	7.15	90.38	30.17	1.40	59.34
1.4-1.5	13.74	14.72	68.96	8.66	44.78	53.08	1.50	18.07
1.5-1.6	4.33	24.66	73.29	9.60	31.04	70.06	1.60	6.27
1.6-1.8	3.87	36.89	77.16	10.97	26.71	77.41	1.70	3.87
1.8-2.0	1.58	55.63	78.74	11.87	22.84	84.28	1.90	1.58
>2.0	21.26	86.41	100.00	27.72	21.26	86.41		
Total	100	27.72						
Coal slurry	7.78	29.26						
Total	100	27.84						

The washability curves are mainly composed of an elementary ash curve, an accumulative floats curve, an accumulative sinks curve, a density curve, and a near-density curve. It could be assumed that the theoretical yield of the cleaning coal could achieve more than 75% with an ash content of 10.0% at a separating density of 1.71 g/cm^3. The fine coal sample belongs to the moderate difficulty for separation. Additionally, as the quality of cleaning coal increases, the recovery of cleaning coal decreases and the washability of fine coal sample drops.

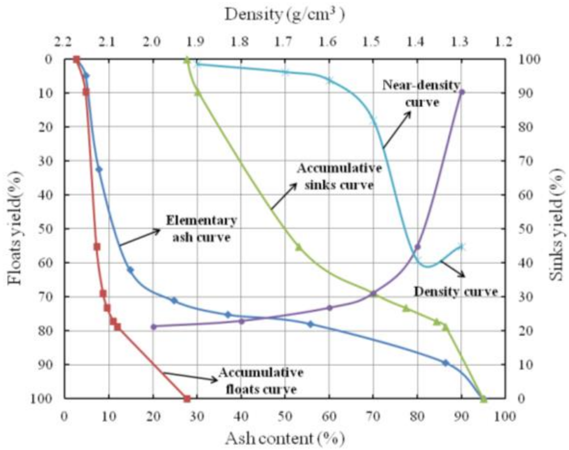


Fig. 1. Washability curves of 6-1mm fine coal sample

Experimental apparatus

Figure 1 illustrates the experimental apparatus of the vibration fluidized bed. It mainly consists of an air supply and control system, vibration fluidized bed separator, measurement devices of bed pressure drop and density, control and adjusting system of vibration parameters. A cylindrical fluidized bed with a diameter of 160 mm and height of 500 mm was designed and installed on the vibration platform. The compressed air generated by a fan blower is pushed into an air buffer, and then transported into the fluidized bed uniformly through a gas distributor located at bed bottom. The gas distributor is composed of double layer filtration fabric and single layer steel wire gauze. The air flowrate is controlled by an air valve, and a rotermeter is used to adjust the gas velocity within a suitable variation range. The pressure drops at different bed heights are measured by the pressure transducer. The bed densities at different bed positions are measured by a group of portable densitometer. The vibration amplitude and frequency of fluidized bed are adjusted by the computer controlling system. The magnetite powder with a wide size range was fed into the fluidized bed initially. The bed expansion height and pressure drops are measured after achieving stable fluidization status. 6-1mm fine coal was a sample fed into bed to carry out the separating experiments. The fine coal sample stratifies by density differences after a certain separating period. Finally, the fine coal samples at different layers of bed interspaces are taken and tested to compare and verify the separation efficiency.

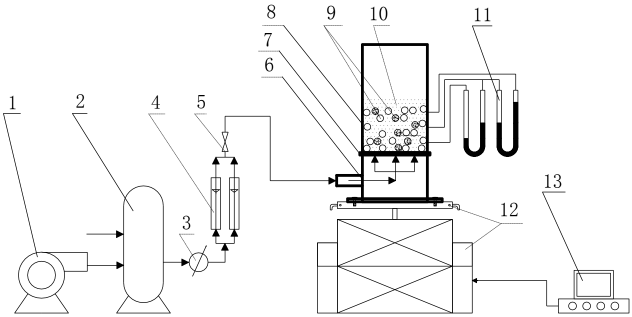


Fig. 2. Experimental apparatus of vibration fluidized bed
1. Fan blower, 2. Air buffer, 3. Air valve, 4. Rotemeter, 5. Butterfly valve, 6. Air chamber, 7. Gas distributor, 8. Fluidized bed separator, 9. Fine coal sample, 10. Separating medium solids, 11. Pressure transducer, 12. Vibration platform, 13. Vibration control and adjusting system

Evaluation approach

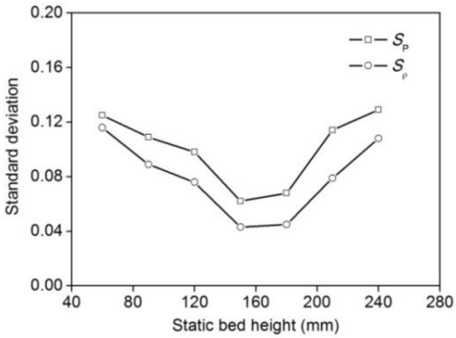
Bed pressure drop and density distribution are major indicators to evaluate the fluidization quality in DMGFB. Therefore, the standard deviations of pressure drops and densities at different bed positions are proposed to characterize the fluidization stability and density uniformity in the interspaces of bed.

The mean bed pressure is $\overline{P}=\frac{1}{n}\sum_{i=1}^{n}P_i$, standard deviation of bed pressure drops $S_P=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i-\overline{P})}$, mean bed density $\overline{\rho}=\frac{1}{n}\sum_{i=1}^{n}\rho_i$, standard deviation of bed densities $S_\rho=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(\rho_i-\overline{\rho})}$ where, P_{i} and ρ_{i} refer to the instantaneous values in position i, $\overline{P}$ and $\overline{\rho}$ refer to the mean values, n refers to the sample numbers of different positions in bed.

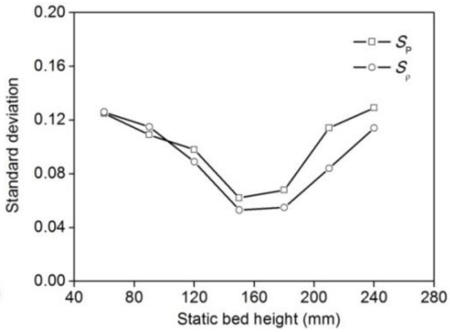
Results and Discussion

Fluidization stability and density distribution uniformity in the bed without vibration

The major factors influencing the fluidization quality of the bed without vibration are the static bed height and superficial gas velocity. The static bed height H_{s} of 60, 90, 120, 150, 180, 210 and 240 mm were selected, respectively. The minimum fluidization velocity U_{mf} of the bed is 7.2 cm/s at H_{s} = 150 mm. The research achievements indicate that the superficial gas velocity U, should be adjusted in the range of U = 1.6–2.0U_{mf} in order to maintain a stable fluidization (He, 2012). Firstly, the effects of the static bed heights on the fluidization quality and density uniformity were investigated at U = 1.8U_{mf} and 1.9U_{mf}, respectively, as shown in Fig. 3(a) and Fig.3(b). When U = 1.8U_{mf}, the standard deviation of bed pressure drops S_P decreases sharply from 0.125 to 0.062Kpa with increasing static bed height H_s from 60 to 150mm. Then, S_P increases sharply from 0.068 to 0.129 kPa with increasing H_s from 180 to 240 mm. It indicates that the bed maintains stable fluctuations of pressure drop with a static bed height H_s of 150-180 mm. Similarly, the standard deviation of bed densities S_ρ varies from 0.043 to 0.045g/cm^3 with H_s increasing from 150 to 180 mm, which also indicates a uniform density distribution. The similar conclusion is obtained by analyzing the results at U = 1.9 U_{mf}, as shown in Fig. 3(b). Thus, the static bed height should be adjusted in the range of 150-180 mm in this study.



(a)



(b)

Fig. 3. Effect of the static bed height on the fluidization quality and density uniformity

Figure 4 illustrates the standard deviations of bed pressure drop S_P and bed density S_ρ with different static bed heights H_s of 150, 160, 170, 180 mm at U = 1.7-2.0 U_{mf}, respectively. Overall, the values of S_P and S_ρ increase slightly with the H_s increasing from 150 to 180mm. It means that the fluctuations of bed pressure drops and densities increase slightly. The reason is that the distance of the rising bubbles passing through the bed increases with the increasing of H_s. It leads to an intense bubble kinetic behavior and the back-mixing of fine medium solids. Thus, the stability of the whole bed decreases slightly. However, as H_s vary in a suitable extent, the value of S_P maintains stable variation of 0.06–0.08 kPa, and the value of S_ρ also shows steady variation of 0.04–0.07 g/cm^3. Especially, when U = 1.8U_{mf} (12.96 cm/s), the optimal S_P and S_ρ values of 0.062 Kpa and 0.043 g/cm^3 are acquired at H_s = 150 mm. The results indicate that the favorable fluidization stability and uniform density distribution could be achieved by setting a suitable static bed height and selecting a reasonable superficial gas velocity.

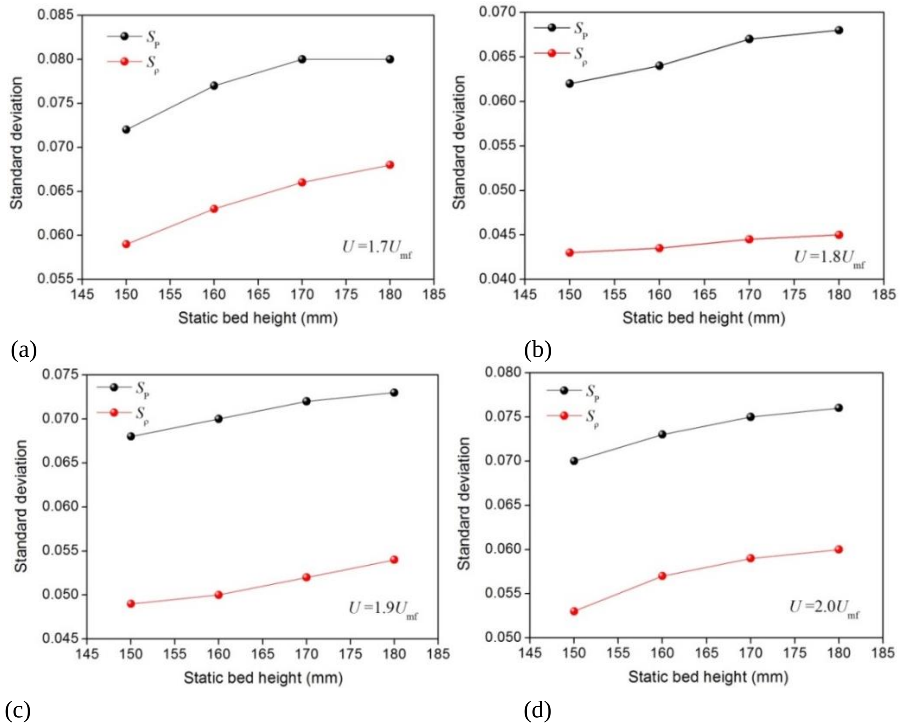


Fig. 4. The standard deviations of bed pressure drop S_P and bed density S_ρ at different gas velocity

Fluidization stability and density distribution uniformity in vibration bed

Based on the traditional DMGFB, the vibration energy is introduced to improve the fluidization quality and separation efficiency. The major factors influencing the fluidization quality include the vibration amplitude, vibration frequency, static bed height and superficial gas velocity. In order to examine the effects of above factors on the fluidization quality, a group of orthogonal experiment was designed to verify the S_P and S_ρ values under different operating conditions. Table 3 shows the levels of the factors used in the experiment. Four levels were selected for each factor. The designed experimental program and analyzed results of orthogonal experiment are listed in Table 4. 16 interactive experiments were designed and conducted under different operating conditions, and the values of S_P and S_ρ were obtained in each experiment. The analyzed results show that the value of S_P mainly distributes in the range of 0.034–0.072 kPa, and S_ρ value of 0.018–0.056 g/cm^3. The analysis of a variance approach is applied to verify the significance of four factors. The analyzed results are shown in Table 5, among which, F value represents the significance of different factor. Normally, the larger the F value is, the more significance of the factor is emphasized. Hence, it could be obtained that the significance of four factors appears vibration amplitude A > superficial gas velocity U > vibration frequency f > static bed height H_s. The most significant factors influencing the fluidization quality are vibration amplitude A and superficial gas velocity U with the F values of 4.42 and 4.11, respectively. The static bed height H_s shows the least influence. Therefore, factors of A and U should be considered as the most important operating condition in vibration bed. In the orthogonal experiment, the optimal S_P and S_ρ values of 0.034 kPa and 0.018 g/cm^3 are acquired with the operating factors of A = 1mm, $U = 1.8U_{mf}$, f = 15 Hz and H_s = 150 mm, respectively.

Table 3. The levels of different factors used in the experiment

No.	Factors			
	Vibration amplitude A (mm)	Vibration frequency f (Hz)	Static bed height H_s (mm)	Superficial gas velocity U (cm/s)
1	1	10	120	1.7 U_{mf}
2	2	15	150	1.8 U_{mf}
3	3	20	180	1.9 U_{mf}
4	4	25	210	2.0 U_{mf}

Table 4. The designed program and results of orthogonal experiment

No.	Factors				Evaluation indexes	
	Vibration amplitude A (mm)	Vibration frequency f (Hz)	Static bed height H_s (mm)	Superficial gas velocity U (cm/s)	S_P (Kpa)	S_ρ (g/cm^3)
1	1	10	120	1.7 U_{mf}	0.037	0.023
2	1	15	150	1.8 U_{mf}	0.034	0.018
3	1	20	180	1.9 U_{mf}	0.041	0.029
4	1	25	210	2.0 U_{mf}	0.052	0.046
5	2	10	150	1.9 U_{mf}	0.039	0.024
6	2	15	120	2.0 U_{mf}	0.050	0.043
7	2	20	210	1.7 U_{mf}	0.037	0.022
8	2	25	180	1.8 U_{mf}	0.039	0.025
9	3	10	180	2.0 U_{mf}	0.043	0.030
10	3	15	210	1.9 U_{mf}	0.048	0.035
11	3	20	120	1.8 U_{mf}	0.067	0.053
12	3	25	150	1.7 U_{mf}	0.055	0.045
13	4	10	210	1.8 U_{mf}	0.063	0.048
14	4	15	180	1.7 U_{mf}	0.051	0.039
15	4	20	150	2.0 U_{mf}	0.072	0.056
16	4	25	120	1.9 U_{mf}	0.054	0.041

Table 5. Analysis of variance for the orthogonal experiment

Variance source	Sum of squares	Degrees of freedom	Mean square	*F* value	Confidence interval of *F* value	Significance
A	$2.4e^{-3}$	3	$8.14e^{-4}$	4.42	[3.86,6.99]	Significant
f	$6.38e^{-4}$	3	$2.13e^{-4}$	1.15	[3.86,6.99]	--
H_s	$3.21e^{-4}$	3	$1.07e^{-4}$	0.58	[3.86,6.99]	--
U	$2.3e^{-3}$	3	$7.57e^{-4}$	4.11	[3.86,6.99]	Significant
Error	$1.7e^{-3}$	9	$1.84e^{-4}$			
Sum	$6.4e^{-3}$	15				

Comparison of bed stability and density uniformity in the bed with and without vibration

Bed stability and density uniformity in the bed with and without vibration were compared to investigate the effect of the vibration energy. Under the optimal operating conditions, the pressure drop fluctuation of the whole bed was compared with and without vibration, as presented in Fig. 5. In general, the pressure drop of the bed without vibration is approximate 6.6 kPa after achieving a stable fluidization. It is a little larger than the bed pressure drop of 5.6 kPa in vibration bed. The minimal fluidization velocity U_{mf} of the bed without vibration is 7.2 cm/s, which is also lager than U_{mf} of 4.9 cm/s in vibration bed. Comparing with the bed without vibration, introducing the vibration energy obviously lowers bed pressure drop and decreases the minimum of the fluidized velocity of the bed. It is because that the effect of vibration energy enhances the collision and friction between the fine medium solids, which leads to a great loose effect on the static packed bed. It provides a favorable condition for the gas to overcome the bed resistance and pass through the interspace of the packed fine powders. As the enhancement of the interaction between the vibration energy and gas, the whole bed changes to a complete fluidization state gradually. At the moment, fine medium solids in the bed were held up with the effects of gas and effective excitation force. Then, the movement behaviors of fine particles change to the free-moving states with the effects of their own natural vibration. Therefore, the bed not only shows favorable stability across its whole space, but also owns sufficient activity. It is greatly conducive to the effective separation of 6-1 mm fine coal.

Additionally, it has an obvious turning point of bed pressure drop before achieving a stable fluidization of the bed without fluidization. The fluctuation of bed pressure drop is a little intense at $U < 1.7U_{mf}$ (12.24 cm/s). However, it shows a smooth transition when achieving stable fluidization in vibration bed. The bed pressure drop maintains a steady variation with less fluctuation for the increase of gas velocity after achieving U_{mf} (4.9 cm/s). It also indicates that the vibration energy is helpful to form good fluidization quality at a smaller gas velocity in a short period. If increasing the vibration amplitude and superficial gas velocity further, the collision and friction between the fine powders will become more intense, resulting in the exacerbation of back-mixing of medium solids. Besides, as the increasing of gas velocity, the bubble quantity and sizes will increase rapidly and the bubble kinetic behaviors will become more complex and confused. These performances of fine medium solids and rising bubbles worsen the fluidization quality and density uniformity in bed. Thus, the significant factors of vibration amplitude A and superficial gas velocity U should be adjusted in a suitable variation range so as to maintain the bed stability and density uniformity in vibration bed.

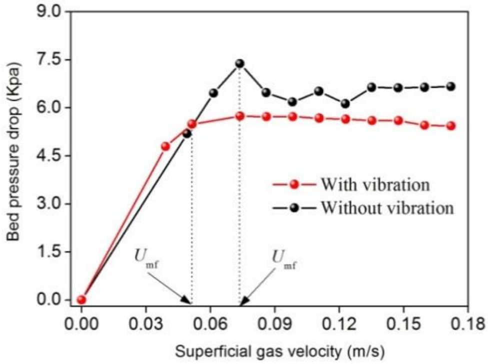
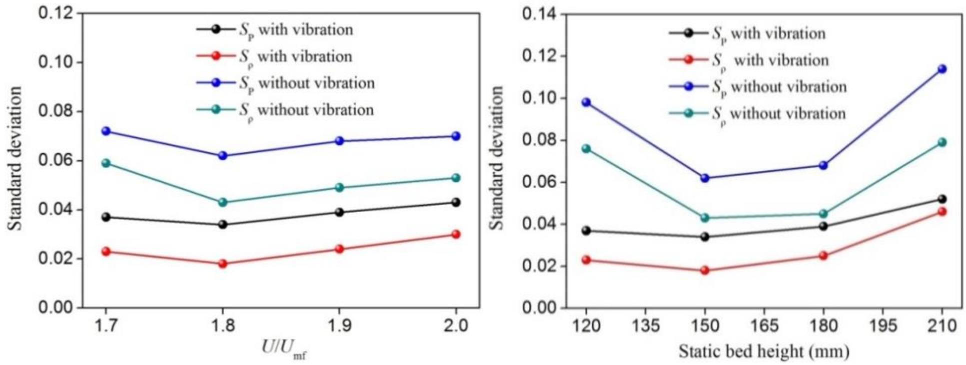


Fig. 5. Pressure drop fluctuation of the bed with and without vibration



(a) (b)

Fig. 6. Comparison results of S_P and S_ρ values in the bed with and without vibration

The comparison of the standard deviations of bed pressure drop S_P and bed density S_ρ are presented in Fig. 6. The values of S_P and S_ρ in the bed with and without vibration were compared at U = 1.7, 1.8, 1.9 and 2.0U_{mf}, respectively, as shown in Fig. 6(a). The S_P and S_ρ values in the vibration bed are obviously smaller than the values without vibration. The optimal S_P and S_ρ values of 0.034 kPa and 0.018 g/cm^3 with vibration are much smaller than the optimal values of 0.062 kPa and 0.043 g/cm^3 without the vibration at U = 1.8U_{mf}. Comparing with the bed without vibration, S_P and S_ρ values reduce sharply by 45.2% and 58.1%. This indicates a more stable fluidization quality and uniform density distribution in vibration bed. The values of S_P and S_ρ in the bed with and without vibration were also compared at different static bed height H_s of 120, 150, 180 and 210 mm, respectively, as shown in Fig. 6(b). Similarly, the comparison of the results shows that the S_P and S_ρ values are obviously smaller in vibration bed. The optimal S_P and S_ρ values reduce sharply by 45.2% and 58.1% as well at H_s = 150 mm. Thus, the vibration energy with a suitable vibration amplitude and frequency should be introduced to DMGFB for better fluidization quality and separation efficiency.

Comparison of separation performance of 6-1mm fine coal in the bed with and without vibration

The separation performance of 6-1 mm fine coal sample from Yongcheng (China) applying the fluidized bed with and without vibration were compared and analyzed with the optimal operating conditions. The detailed operating parameters in the separation experiments are listed in Table 6.

Table 6. Detailed operating parameters in separation experiments

Operating parameter	Without vibration	With vibration
Vibration amplitude A (mm)	0	1
Superficial gas velocity U (cm/s)	12.96	8.82
Vibration frequency f (Hz)	0	10
Static bed height H_s (mm)	150	150
Separating time T (s)	60	60

After achieving stable fluidization, a certain amount of 6-1mm fine coal sample was fed into the fluidized bed separator with and without the vibration, respectively. After the separating time of 60 seconds, the feedstock stratifies by the density differences. Then, the products distributing in different layers of the bed were removed from the bed to carry out the float-sink experiments. The partition curves of the separation experiments are shown in Fig. 7.

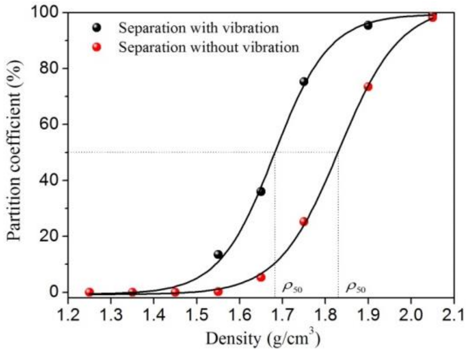


Fig. 7. Partition curves of the separation experiments with and without vibration

The partition coefficient represents the mass fraction of coal particles reporting to the tailing. The coal particles with 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* could be calculated as $(\rho_{75} - \rho_{25})/2$. The lower *E* value indicates the better separation performance. The ash content of 6–1mm fine coal was reduced from 27.84% to 9.50% at a separating density of 1.68 g/cm^3 in the separation experiments with vibration. The probable error *E* shows 0.505, which is much lower than the *E* value of 0.9 in the separation experiments without vibration. It demonstrates that the vibration fluidized bed performs favorable separation efficiency of 6-1mm fine coal.

Conclusions

The vibration amplitude *A* and superficial gas velocity *U* are the most significant factors influencing the fluidization stability and density distribution uniformity. The optimal operating factors are A = 1 mm, U = 1.8 U_{mf}, f = 15 Hz and H_s = 150 mm with S_P and S_ρ values of 0.034 kPa and 0.018 g/cm^3, respectively.

Comparing with the bed without vibration, the minimum fluidization velocity U_{mf} was lowered from 7.2 to 4.9 cm/s, and the optimal values of S_P and S_ρ reduced sharply by 45.2% and 58.1% at H_s = 150 mm. It indicates that introducing a vibration energy to the bed could effectively improve the fluidization quality and separation density environment.

The ash content of 6-1mm fine coal from Yongcheng (China) was reduced from 27.84% to 9.50% at a separating density of 1.68 g/cm^3 in the separation experiments with vibration. A probable error *E* value of 0.505 was achieved, indicating a favorable separation performance in vibration bed. This technology provides a novel approach to deal with the 6-1 mm fine coal in arid and water-shortage areas.

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References

BROZEK M., MLYNARCZYKOWSKA A., 2013. *An analysis of effect of particle size on batch floatation of coal*. Physicochemical Problems of Mineral Processing, 49(1), 341–356.

CHEN Q.R., YANG Y., 2003. *Development of dry beneficiation of coal in China*. Coal Preparation, 23(1-2), 3-12.

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. (In Chinese)

HE J.F., HE Y.Q., ZHAO Y.M., DUAN C.L., YE C.L., 2012. *Numerical simulation of the pulsing air separation field based on CFD*. International Journal of Mining Science and Technology, 22(2), 201-207.

HE J.F., ZHAO Y.M., HE Y.Q., LUO Z.F., DUAN C.L., 2013b. *Fluidization characteristics of the dense Gas-solid fluidized bed separator based on the Mixed-medium solids of magnetite and paigeite powder*. International Journal of Coal Preparation and Utilization, 33 (5), 225-241.

HE J.F., ZHAO Y.M., HE Y.Q., LUO Z.F., DUAN C.L., 2013c. *Separation performance of raw coal from South Africa using the dense gas-solid fluidized bed beneficiation technique*. Journal of The Southern African Institute of Mining and Metallurgy, 113 (7), 575-582.

HE J.F., ZHAO Y.M., HE Y.Q., LUO Z.F., DUAN C.L., 2014. *Force characteristic of the large coal particle moving in a dense medium gas-solid fluidized bed*. Powder Technology, 254, 548-555.

HE J.F., ZHAO Y.M., HE Y.Q., WALZEL P., SCHALDACH G., DUAN C.L., 2013a. *Force measurement and calculation of the large immersed particle in dense gas-solid fluidized bed*. Powder Technology, 241, 204-210.

HE J.F., ZHAO Y.M., LUO Z.F., HE Y.Q., DUAN C.L., 2013d. *Numerical simulation and experimental verification of bubble size distribution in an air dense medium fluidized bed*. International Journal of Mining Science and Technology, 23 (3) ,387-393.

LUO Z.F, ZHAO Y.M., 2002. *Beneficiation Theory of Fluidization*. China University of Mining and Technology Press, Xuzhou, China. (In Chinese)

LUO Z.F, ZHAO Y.M., CHEN Q.R., FAN M.M., TAO X.X., 2002. *Separation characteristics for fine coal of the magnetically fluidized bed*. Fuel Processing and Technology, 79(1), 63-69.

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., CHEN Q.R., 2001. *Effect of fine coal accumulation on dense phase fluidized bed performance*. International Journal of Mineral Processing, 63(2), 217-224.

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 (2) , 119-123.

MACPHERSON S.A., IVESON S.M., GALVIN K.P., 2010. *Density based separations in the Reflux Classifier with an air-sand dense-medium and vibration*. Minerals Engineering, 23, 74-82.

NAKHAEI F., IRANNAJAD M., 2013. *Prediction of on-line froth depth measurement errors in industrial flotation columns: a promising tool for automatic control*. Physicochemical Problems of Mineral Processing, 49(2), 757–768.

PRASHANT D., XU Z., SZYMANSKI J., GUPTA R., BODDEZ J., 2010. *Dry cleaning of coal by a laboratory continuous Air Dense Medium Fluidized Bed separator*. 2010 International Coal Preparation Congress, Lexington, America.

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 (3-4), 127-148.

SAMPAIO C.H., ALIAGA W., PACHECO E.T., PETTER E., WOTRUBA H.,2008. *Coal beneficiation of Candiota mine by dry jigging*. Fuel Processing Technology, 89(2),198-202.

SVOBODA J., COETZEE C., CAMPBELL Q.P., 1998. *Experimental investigation into the application of a magnetic cyclone for dense medium separation*. Minerals Engineering, 11(6), 501-509.

TAKANA Z., SATO H., KAWAI M., OKADA K., TAKAHASHI T, 1996. *Dry Coal Cleaning Process for High-quality Coal*. Journal of chemical engineering of Japan, 29(2), 257–263.

WEITKAMPER L., WOTRUBA H., SAMPAIO C.H., 2010. *Effective dry density beneficiation of fine coal using a new developed fluidized bed separator*. 2010 International Coal Preparation Congress, Lexington, America.

ZHAO Y.M., LUO Z.F., CHEN Q.R., 2004. *Fundamental and practical developments of dry coal cleaning in China: a Review*. Coal Preparation Society of America Journal, 3 (3), 14-18.

ZHAO Y.M., TANG L.G., LUO Z.F., LIANG C.C., XING H.B., DUAN C.L., SONG S.L., 2012. *Fluidization characteristics of a fine magnetite powder fluidized bed for density-based dry separation of coal*. Separation Science and Technology , 47 (16), 2256-2261.

ZOU W.J., CAO Y.J., ZHANG Z.J., LIU J.T., 2013. *Coal petrology characteristics of middlings from Qianjiaying fat coal mine*. International Journal of Mining Science and Technology, 23 (5) ,777-782.