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# COMPARATIVE ANALYSIS OF COAL BENEFICIATION PERFORMANCE IN GAS-SOLID FLUIDIZED SEPARATION BEDS WITH DIFFERENT BED STRUCTURES

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## Abstract

Fluidization characteristics and separation properties of fluidized beds with different bed structures were studied. The stability of fluidized beds with different structures decreases with the increase of bed height. The uniformity and stability of density of rectangular fluidized bed is better than that of square and circular fluidized bed at the same bed height. The influence of fine coal content on the density distribution of fluidized bed has little relation with the bed structure. Separation results showed that ash segregation degrees of the three fluidized beds were generally high and the separation effects were good when the static bed height was 130 mm, the fluidization number was 1.5, and the fine coal content was 10%. The rectangular gas-solid fluidized bed has the best separation effect: the lowest ash content of cleaned coal is 20.11% and the probable error $E_p$ is 0.11g/cm$^3$. Its $E_p$ value is significantly better than that of square fluidized bed ($E_p$=0.155 g/cm$^3$) or circular fluidized bed ($E_p$=0.16 g/cm$^3$).

*Key words:* bed structure, density separation, fluidization characteristic, gas-solid fluidized separation bed, separation experiment

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## 1. Introduction

Coal is a major energy source in China and plays a significant role in the development of the overall national economy. However, coal combustion and processing inevitably worsen the environment. Therefore, it is necessary to utilize coal efficiently and cleanly. Currently, wet coal separation is one of the clean coal technologies, but it causes both water waste and water pollution (Shahhosseini et al., 2016; Xue et al., 2011; Zhao, 2011). China's coal mainly distributes in the arid northwest region, where water resources are scarce. This makes it difficult to popularize wet separation technology in this area. On the contrary, dry coal beneficiation technology is being rapidly developed. Because this process does not use water for separation, it is of great interest to the coal preparation industry. In particular, fluidized dry separation technologies performed in gas-solid fluidized separation beds are gradually being popularized and applied (Dwari and Rao, 2007; Mohanta et al., 2013; Singh and Rao, 2010; Tan et al., 2017; Wei et al., 2017; Zhang et al., 2017).

To improve the beneficiation scale of gas-solid fluidized separation beds, and enhance the separation adjustability of difficult-to-separate coals, researchers have investigated the characteristics and separation performance of gas-solid fluidized separation beds. These researches focused on various factors of fluidized bed, including gas velocity (Gosavi et al., 2018; Wang et al., 2010; Zhou et al., 2018), characteristics of dense medium (Ding et al., 2011; Fu et al., 2013; Tan et al., 2017), external forces (Luo et al., 2008; Song et al., 2012; Yang et al., 2017) etc. The structure of a fluidized bed is fixed during separation

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processes, so its effects on the separation behavior of gas-solid fluidized beds are often ignored.

The effects of the structure on fluidized beds particularly used in the chemical industry have been investigated by some researchers. Afrooz et al. (2017) studied the effects of swirling structure on the hydrodynamics behavior of bubbling fluidized beds by simulation software. The results showed that the geometry of swirling tube improved the rotating flow of particles, and this rotary motion promoted the radial gas-solid mixing, thereby increasing particle residence time. By combining numerical simulations and experimental methods, Chu and Yu (2014) developed an S-shaped structure that can significantly promote the uniform distribution of solid particles in a circulating fluidized bed, further eliminating the nuclear-ring flow structure that exists in normal fluidized beds. Park and Hang (2013) studied the mixing-segregation behavior of fluidized materials and coke particles in fluidized bed reactors with different column shapes, and demonstrated that cylindrical structures produced the lowest mixing index during the material segregation stage.

Sahu et al. (2013) deemed that bed structure had a great influence on the fluidization properties of fluidized beds. The fluidized beds with rectangular sections have better stability than those with circular and square sections. In this paper, we investigated the effects of bed structure on the fluidization characteristics and beneficiation performance of fluidized beds by using three different bed structures (square, circular, and rectangular). Bed fluidization uniformity was indicated by bed density, minimum fluidized gas velocity etc. We expected to find the suitable beneficiation conditions (i.e., static bed height, fine coal content, fluidization number etc.) which would improve the separation efficiency of the fluidized bed. The fluidization number is the ratio of the operating gas velocity to the minimum fluidized gas velocity. We also compared the separation performance of three different fluidized bed structures to provide a basis for creating a good fluidization state and optimizing the structure of equipment.

## 2. Experimental system and materials

### *2.1. Experimental system*

The experimental system consists primarily of a gas supply system, a separation system, and a measuring system, as shown in Fig. 1. The gas supply system consists of a blower, wind pack, rotameter, etc. The separation system includes a gas distribution chamber, air distribution board, and bed made of transparent organic glass. The primary test device is u-tubes, which is used to observe pressure changes in the fluidized bed during the experimental process.

In the tests, the velocity of gas entering the fluidized bed was controlled by a rotameter. To study the effects of bed structure on the fluidization characteristics, we investigated three different bed structures: square (170×170×500 mm), circular (inner diameter 170 mm, height 500 mm) and rectangular (170×340×500 mm). We determine the length of the square bed, the short side of the rectangular bed, and the diameter of the circular bed are the same value, 170 mm, which serves as the criterion when we study the fluidization characteristics of the three kinds of beds. The fluidized bed was divided into five layers along the bed height to test the pressure drop. The measurement points for each layer were arranged as shown in Fig. 2. The coal samples in the upper two layers were regarded as clean coal, and the lower three layers were regarded as tailings after a period of separation operations.

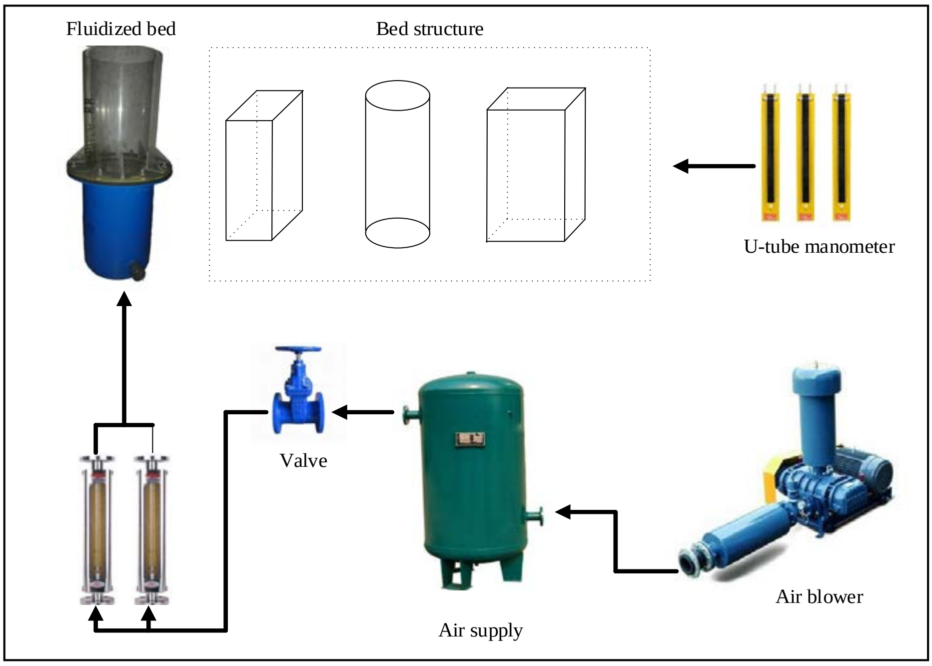
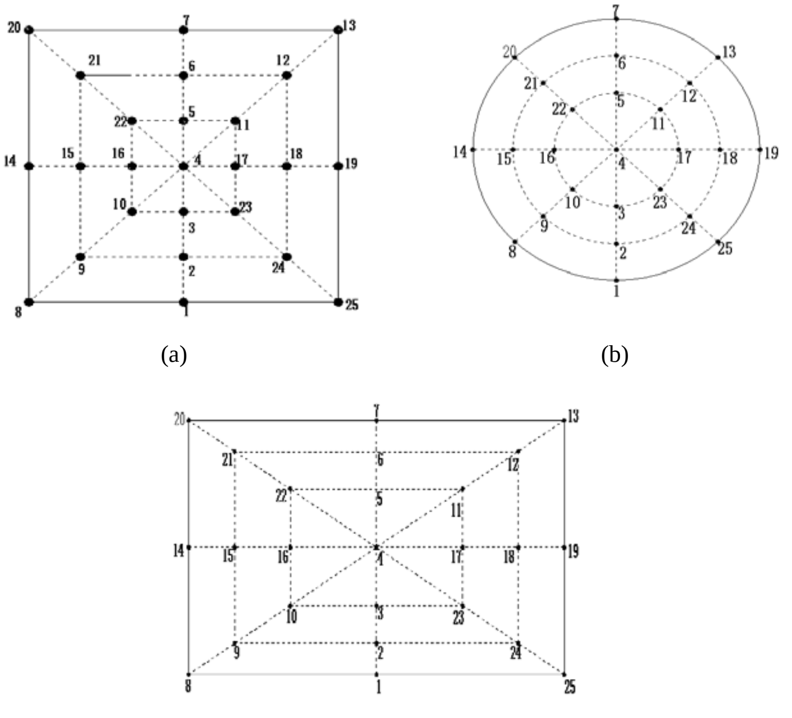


**Fig. 1.** Schematic of gas-solid fluidized bed testing system



(a)

(b)

(c)

**Fig. 2.** Distribution of measurement points in the cross section (a) square bed; (b) circular bed; (c) rectangular bed

### *2.2. Experimental materials*

A binary medium consisted of magnetite powder (bulk density of 2.46g/cm$^3$, porosity of 40.63%) and fine coal (-1+0.5mm) was used as the fluidized medium. The particle size composition of the magnetite powder is presented in Table 1. The data of float-sink test of raw coal (-13+6mm) for separation is presented in Table 2.

**Table 1.** Size composition of magnetite powder

| *Size (mm)* | *Content (%)* |
|---|---|
| +0.3 | 0.09 |
| -0.3+0.15 | 80.21 |
| -0.15+0.074 | 17.60 |
| -0.074 | 2.10 |
| Total | 100.00 |

### *2.3. Evaluation indexes*

Density is the key factor affecting the separation performance of a gas-solid fluidized separation bed. Bed density distributions can be determined from the spatial and temporal pressure drop distributions at various points inside the fluidized bed. Because of the fluid-like characteristics of a fluidized bed, the pressure difference between two adjacent points in the height of the bed is proportional to the bed density and the height difference, which is expressed as (Eq. 1):

$$\Delta P = \rho g \Delta H \tag{1}$$

where: $\Delta P$ is the pressure difference between two adjacent pressure testing points, Pa; $\rho$ is the bed density, kg/m$^3$; $g$ is gravity acceleration, m/s$^2$; and $\Delta H$ is the height difference between two pressure measuring points, m.

To better evaluate the density distribution uniformity of a fluidized bed, the standard deviation of density fluctuation, $S_p$, is introduced and expressed as (Eq. 2). $S_p$ cannot be measured directly, but obtained by calculation after processing the test data.

$$s_p = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\rho_I - \bar{\rho}\right)^2} \tag{2}$$

where $S_p$ is the standard deviation of the bed density distribution; $\rho_i$ is the density of the $i$-th measuring point, g/cm$^3$ ; $\bar{\rho}$ is the average density, g/cm$^3$; and $N$ is total number of testing points.

To better evaluate separation performance, we use a quantitative index: the ash stratification degree, S$_A$. This index is calculated according to the following statistical equation (Eq. 3) (Yang et al., 2013):

$$s_A = \sqrt{\frac{\sum_{i=1}^{n}\left(\frac{A_i}{A_0} - 1\right)^2}{N-1}} \tag{3}$$

where $A_i$ is the coal sample ash of the $i$-th layer; $A_o$ is the raw coal ash; n is the numbers of the bed layers. In this study, the value of n was 4. $A_i$ is equal to $A_o$ when

$S_A$ is zero, which indicates that the ash inside the bed is uniformly distributed and the raw coal cannot be separated in a fluidized bed. The larger the value of $S_A$ is, the better the beneficiation effects is**.**

## 3. Results and discussion

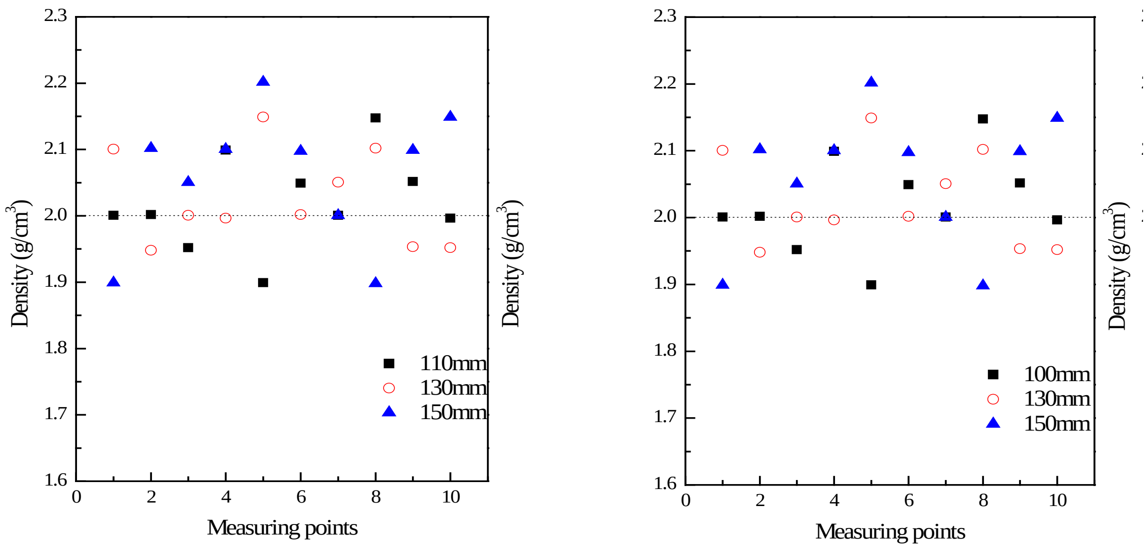
### *3.1. Fluidization characteristics analysis of different bed structures*

In the experiments, the static bed heights were set respectively at 110mm, 130mm, and 150mm for each of the three structures. The density distributions of fluidized beds with different structures are shown in Fig. 3. The standard deviations of bed density increase with the increasing of the bed height. For the bed height of 110 mm, 130 mm, and 150 mm, respectively, the standard deviations of bed density are as follows: square fluidized bed (0.071, 0.076, and 0.091), circular (0.071, 0.072, and 0.099), and rectangular (0.063, 0.057, and 0.075). Obviously, as bed heights increase, the density standard deviations of the fluidized bed increase, indicating the uniformity and stability of the bed decrease. Particularly, the standard deviation of bed density is small when the bed height is lower than 130 mm, indicating the good uniformity and stability of the bed. On the contrary, when the bed height reaches 150mm, the standard deviation obviously increases and the fluctuation range increases dramatically, indicating worse bed stability. Although the increasing of the bed height improves the effective beneficiation area of the bed (Çalban, 2006), it also adds the bed workloads, which is not benefit for the gas distribution in the bed and also affects the uniformity and stability of the bed. Therefore, the static bed height was set as 130mm in further experiments.

The minimum fluidization gas velocity is the main parameter affecting the structure design and craft operations of the fluidized bed. It not only reflects the minimum airflow drag force motivating solid particles into suspension, but also provides a basis for evaluating the fluidization strength of a fluidized bed under high gas-velocity conditions. The minimum fluidization gas velocity generally occurs at the junction of the pressure drop curve of the fixed bed stage and fluidized bed stage. The bed pressure drop variation tendencies are concordant for the three bed structures, i.e. the pressure drop first increases, then decreases, and at last become steady when the gas velocity increases. Results are shown in Fig. 4.

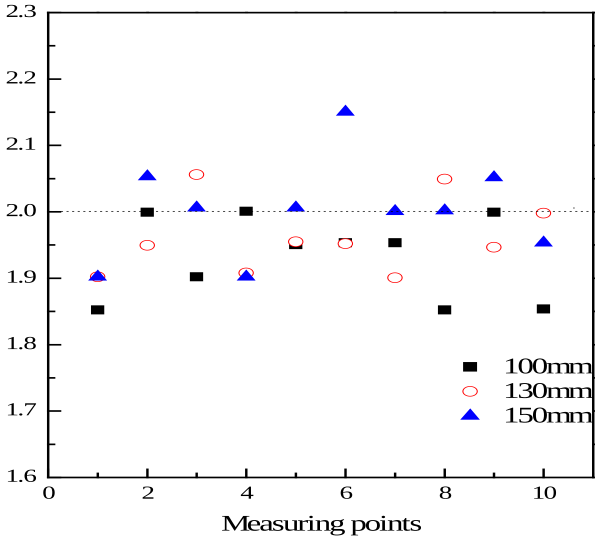
**Table 2.** Float-sink test for coal sample of -13 + 6mm

| ***Density fraction (g/cm³)*** | ***Yield (%)*** | ***Ash (%)*** | ***Floats*** | | ***Sinks*** | | ***Separation density±0.1*** | |
|---|---|---|---|---|---|---|---|---|
| | | | ***Yield (%)*** | ***Ash (%)*** | ***Yield (%)*** | ***Ash (%)*** | ***Density (g/cm³)*** | ***Yield (%)*** |
| -1.4 | 19.54 | 7.80 | 19.54 | 7.80 | 100.00 | 53.35 | 1.4 | 30.43 |
| 1.4-1.5 | 10.89 | 16.72 | 30.43 | 10.99 | 80.46 | 64.42 | 1.5 | 17.03 |
| 1.5-1.6 | 6.14 | 27.95 | 36.57 | 13.83 | 69.57 | 71.88 | 1.6 | 12.97 |
| 1.6-1.8 | 6.83 | 39.35 | 43.40 | 17.85 | 63.43 | 76.14 | 1.7 | 7.38 |
| 1.8-2.0 | 7.93 | 54.59 | 51.33 | 23.53 | 56.60 | 80.58 | 1.9 | 7.93 |
| +2.0 | 48.67 | 84.81 | 100.00 | 53.35 | 48.67 | 84.81 | | |
| Total | 100.00 | 53.35 | | | | | | |



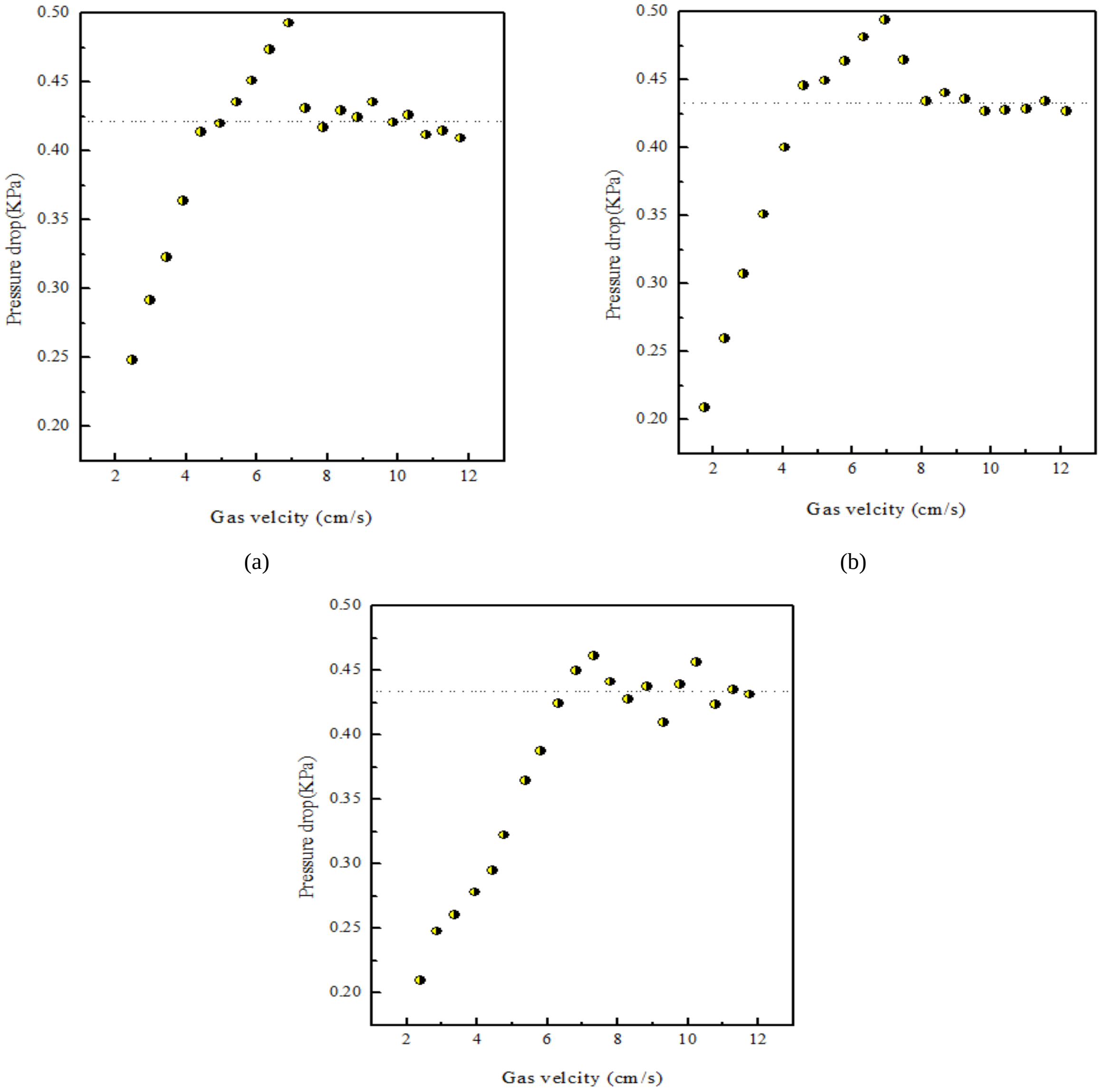
(a)

(b)



(c)

**Fig. 3.** Bed density of different original heights (a) square bed; (b) circular bed; (c) rectangular bed



(a)

(b)

(c)

**Fig. 4**. Fluidization characteristics for different fluidized bed structures (a) square bed; (b) circular bed; (c) rectangular bed

Fig. 5 shows variations in a minimum fluidizing gas velocity with different fine coal content in a bed with different structures. The minimum fluidizing gas velocity of the fluidized bed decreases with increasing of fine coal content because the addition of fine coal broadens the size range of the medium particles and lubricates the fluidized bed. When the fine coal content is 20%, it reaches an approximate saturation in the bed. After that point, variations in the minimum fluidizing gas velocity changes very slowly as more fine coal is added. The minimum fluidizing gas velocity for a rectangular fluidized bed varies greatly with variations of fine coal content. After the fine coal content reaches 20%, the minimum fluidizing gas velocity of the rectangular fluidized bed tends to be consistent with that of the circular bed. Overall, the minimum fluidizing gas velocities for the rectangular and circular fluidized beds are smaller than those for the square fluidized beds. Under the same conditions, the airflow required to fluidize the rectangular and circular beds is smaller than that required to fluidize the square beds. The reason for this phenomenon is that different cross sectional shape of fluidized bed will produce different wall effect. The corners of the square and rectangular fluidized bed will form the dead zone of the fluidized bed, which will affect the initial fluidized gas velocity.

### *3.2. Uniformity and stability in spatial separation density*

For a fluidized bed based on density separation, the uniformity and stability of the spatial bed density is very important, so we studied the density distributions in the whole space of different beds. Fig. 6 shows the cross-sectional density distribution at different height of a square fluidized bed. We can see that the bed densities near the wall are low, while in the center area are high. The reason is the resistance for rising gas caused by the bed wall is small, and the air flux is relatively large, the proportion of gas is larger than that in the central region. In addition, the density uniformity of a fluidized bed under different bed heights is different. The higher the bed height is, the worse the bed density uniformity is. Therefore, bed height should be controlled in a certain range.

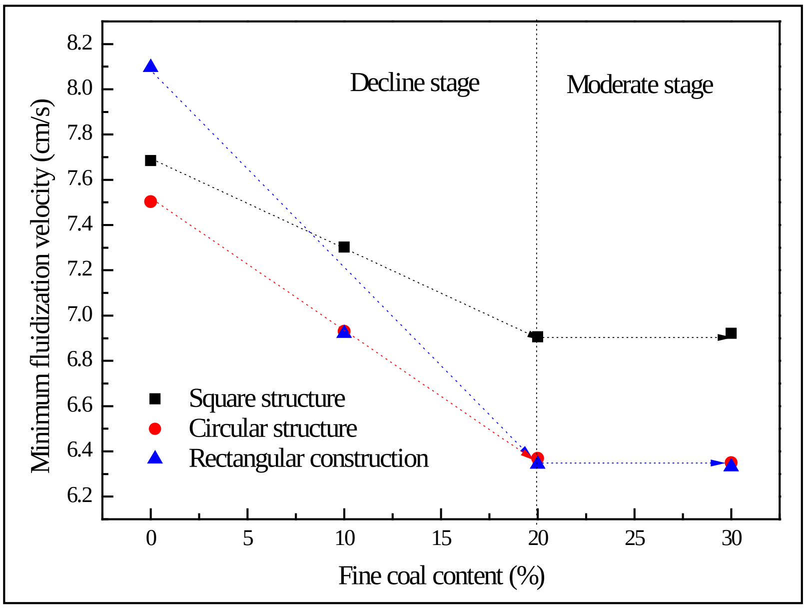
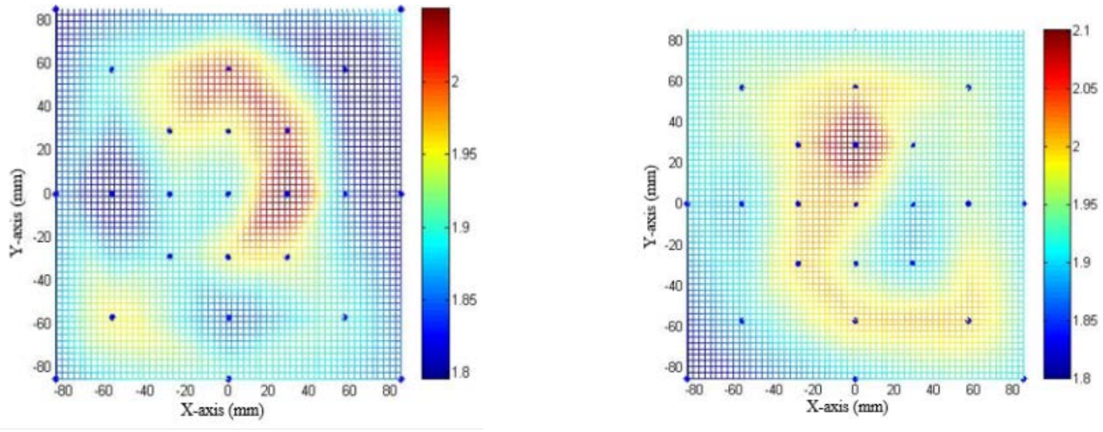
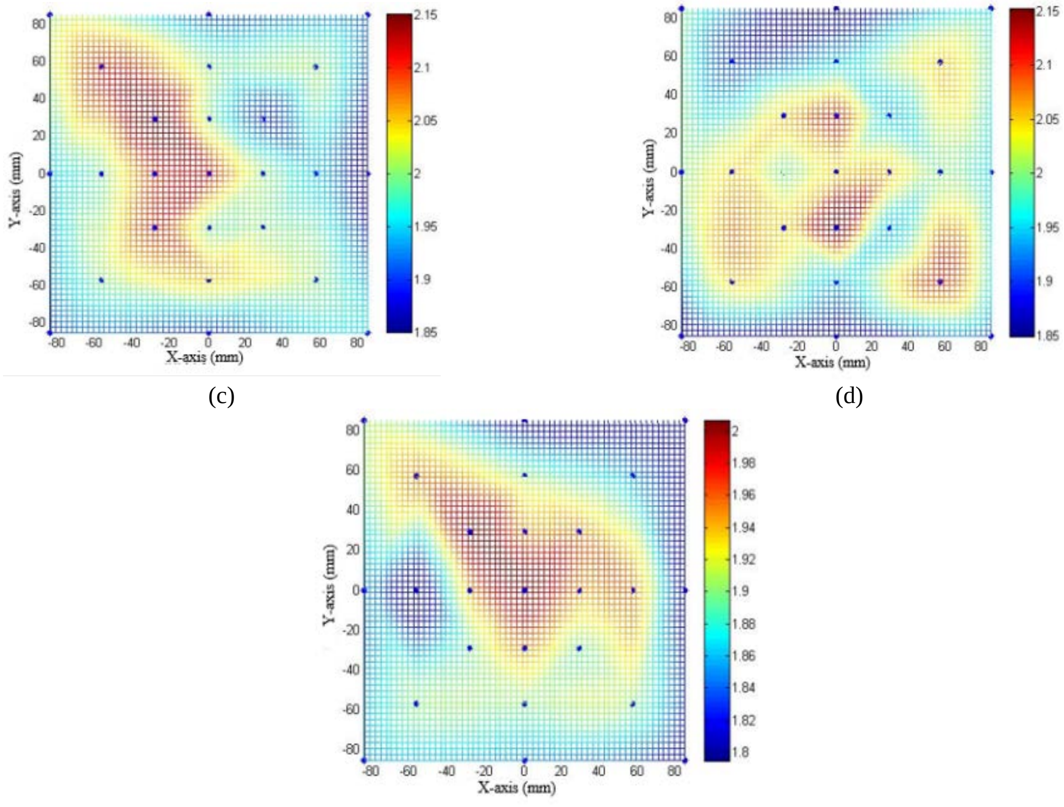


**Fig. 5.** Minimum fluidizing gas velocity for fluidized beds



(a)

(b)



(c)

(d)

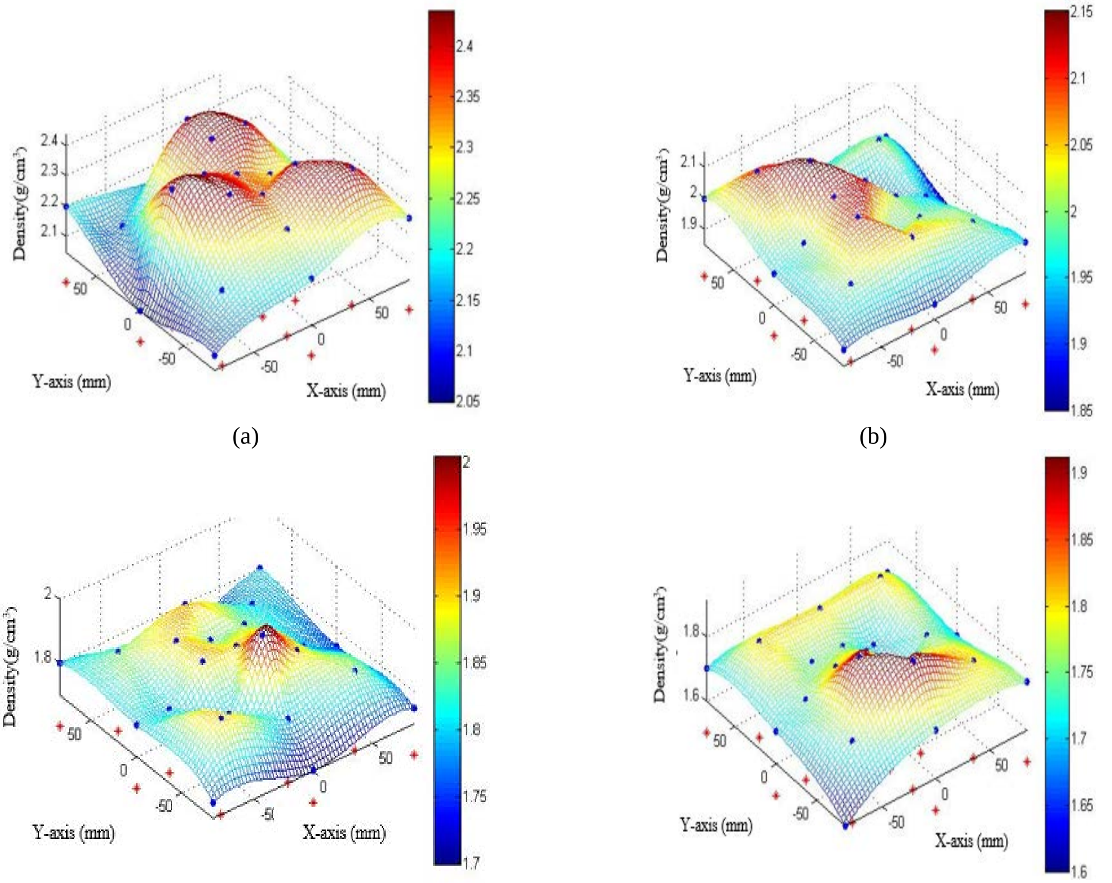
(e)

**Fig. 6.** Bed density distribution at different heights (a) 20mm; (b) 45mm; (c) 70mm; (d) 95mm; (e) 120mm

Fig. 7 shows the density distribution at a bed height of 70 mm of the square fluidized bed with different fine coal contents (wt%). With the increasing of fine coal content, the bed density decreases from 2.27 g/cm$^3$ (at 0% fine coal content) to 1.76 g/cm$^3$ (at 30% fine coal content) showing that fine coal plays an important role in regulating bed density. At the same time, the uniformity of the bed density distribution changes with fine coal content. When the fine coal content is 10%, the $S_p$ is 0.0714, indicating that the fluctuation amplitude of bed density is minimized. However, with the increasing of fine coal content, the uniformity and stability of the bed density worsens. When the fine coal content increases to 30%, the $S_p$ goes up to 0.077. At this condition, the fluidized bed cannot effectively perform separation.

Fig. 8 shows the transverse bed density distribution in three fluidized beds with different bed structures. The densities for square bed, circular bed and rectangular bed are 1.99 g/cm$^3$, 2.06 g/cm$^3$, and 1.95 g/cm$^3$, respectively. Meanwhile the standard deviations of bed density are 0.0714, 0.0736, and 0.0562, respectively. This indicates that the amplitude of bed density fluctuations is minimized and the fluidization effect is improved for rectangular fluidized beds. This primarily because the height–diameter ratio of the rectangular fluidized bed is smaller than the corresponding values for the square and circular fluidized beds, which affects the radial motion of particles in the rectangular bed, weakens the overall back-mixing of the fluidized bed, and stabilizes the bed**.**

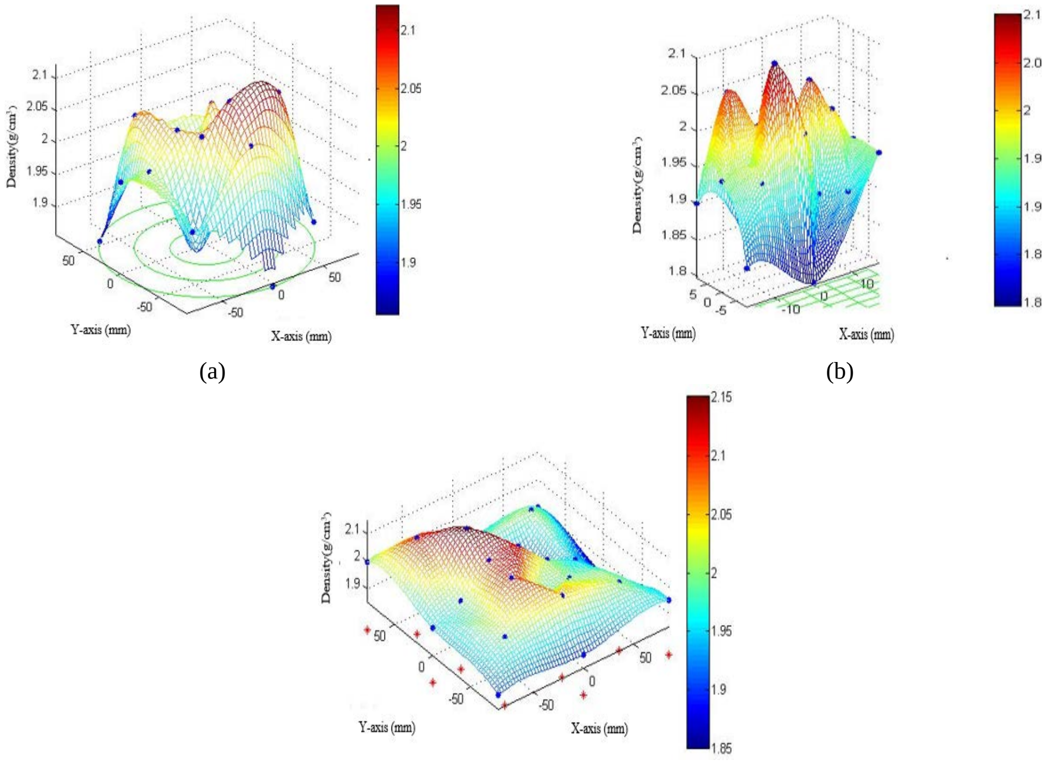
Fig. 9 shows the vertical bed density distributions for different bed structures when the fluidization number is 1.4. When the fine coal contents are 0 and 10%, little changes are observed in the densities of fluidized beds with different structures. When the fine coal content is 0%, the magnetite powder is the only dense medium in the fluidized beds, so the dense medium particles can be uniformly distributed throughout the bed. When the fine coal content is 10%, the dense medium is composed of two-component mixed particles. The small particles fill the voids among the large particles, resulting in a uniform density. Under these conditions, bed densities are similar at each height. When fine coal content is greater than 20%, the fluidization states of beds with different structures tends to be unstable. The smallest size of fine coal and magnetite powder forms the uppermost layer. During the interference sedimentation process of magnetite powder and fine coal, fine coal accumulates in the top layer of the fluidized bed because of its low density, while the magnetite powder accumulates in the top layer of the fluidized bed because of its high density. Moreover, beds with different structures exhibit similar trends for changes in density as fine coal content increase, indicating that the effect of fine coal content on the density distribution of a fluidized bed has little relationship to bed structure.



(a) (b)

(c) (d)

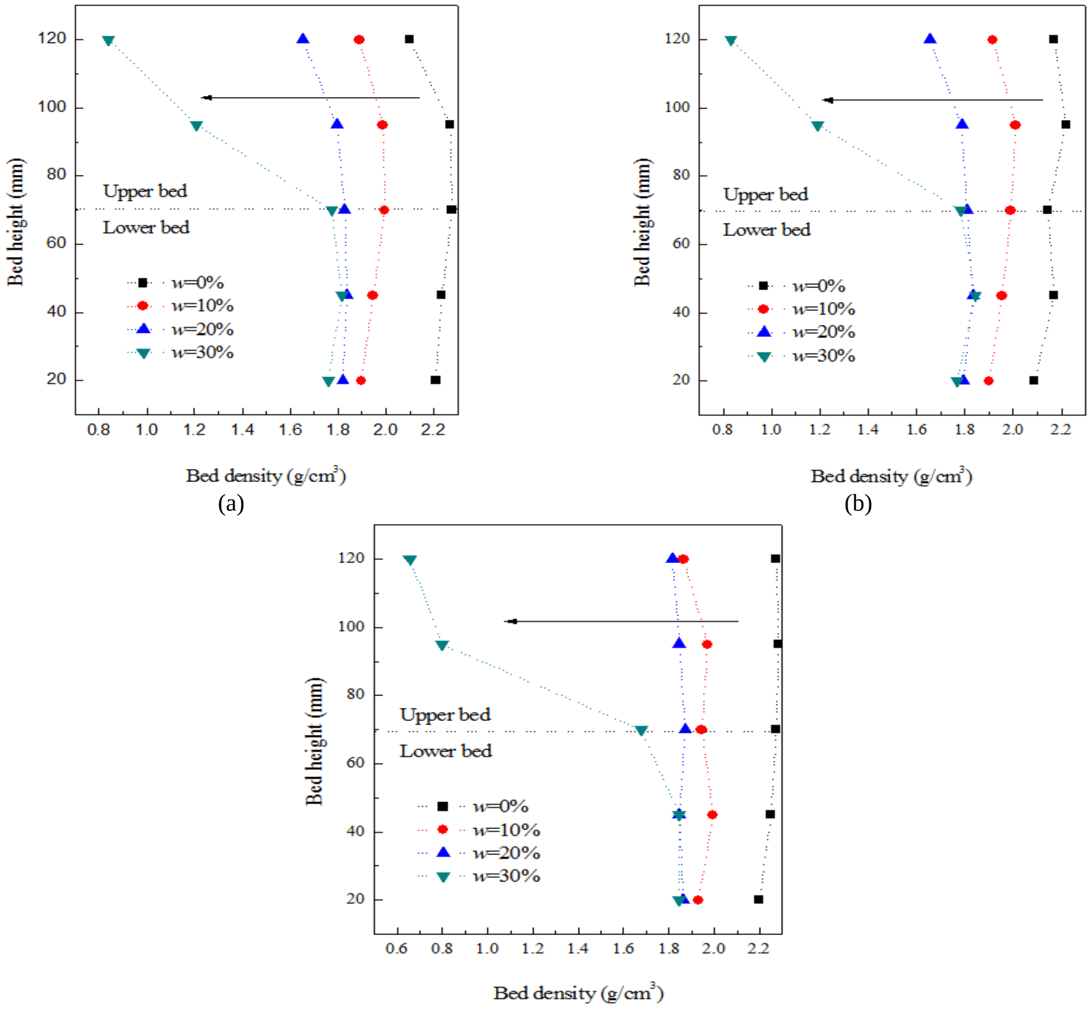
**Fig. 7.** Density distribution of square fluidized bed with different fine coal contents (a) 0%; (b) 10%; (c) 20%; (d) 30%



(a) (b)

(c)

**Fig. 8.** Top view of transverse bed density for different structures (a) square bed; (b) circular bed; (c) rectangular bed



(a) (b) (c)

**Fig. 9.** Vertical density distributions for different fluidized beds (a) square bed; (b) circular bed; (c) rectangular bed

### *3.3. Separation performance analysis of fluidized beds*

Based on the results for fluidization characteristics and exploratory separation experiments, we performed separation studies under different conditions, as presented in Table 3. In general, for a fluidization number of 1.5 and a fine coal content of 10%, the ash stratification degree of a fluidized bed is generally higher, and its separation performance is better. Under lower gas velocity conditions, the bed is incompletely fluidized, and the activity degree of the bed is low. As a result, coal samples with different density composition are not fully separated in the incompletely fluidized bed, and separation performance is poor. At the appropriate gas velocity, the bed activity and fluidization quality are improved, and the coal samples are completely separated. However, at higher gas velocities, the bed activity degrees increase and the mismatch behaviors of coal samples become seriously, resulting in a remixing of the original stratified coal samples. This leads to a deterioration of separation effects. Meanwhile, with the appropriate addition of fine coal ($w$=10%, $w$ is the proportion of fine coal in the dense medium constituted by fine coal and magnetite powder.), the bed activity and fluidization quality improve, because of the differences and complementarity associated with the size and density distributions of the two-component particles in the bed. This effectively leads to separation density adjustments and separation performance. However, excessive fine coal content can generate negative effects, including fluidization imbalances, the stratification of medium particles (magnetite powder and fine coal), and poor bed stability. These characteristics are not conducive for further separation processes.

Based on the above experiments, a static bed height of 130mm, fluidization number of 1.5, and fine coal content of 10% were used as the suitable operating conditions for a separation process of -13+6 mm raw coal in the fluidized bed, as shown in Fig. 10. The probable error values ($E_p$) for the square, circular, and rectangular fluidized beds are 0.155 g/cm$^3$, 0.16 g/cm$^3$, and 0.11g/cm$^3$, respectively. The $E_p$ value of the rectangular fluidized bed is obviously the lowest. Because of the smaller height–diameter ratio, dense medium back-mixing is weaker and the uniformity and stability of bed density is higher. As a result, the separating effects of the rectangular fluidized bed are obviously better than those of the square and circular fluidized beds.

**Table 3**. Separation performance of fluidized beds with different bed structures

| ***Fluidization number*** | ***Fine coal content (%)*** | ***Ash stratification degree*** | | |
|---|---|---|---|---|
| | | ***Square fluidized bed*** | ***Circular fluidized bed*** | ***Rectangular fluidized bed*** |
| 1.4 | 0 | 0.209 | 0.204 | 0.218 |
| 1.4 | 10 | 0.216 | 0.213 | 0.281 |
| 1.4 | 20 | 0.213 | 0.209 | 0.277 |
| 1.5 | 0 | 0.224 | 0.204 | 0.258 |
| 1.5 | 10 | 0.241 | 0.272 | 0.320 |
| 1.5 | 20 | 0.220 | 0.217 | 0.286 |
| 1.6 | 0 | 0.188 | 0.208 | 0.251 |
| 1.6 | 10 | 0.207 | 0.241 | 0.280 |
| 1.6 | 20 | 0.239 | 0.214 | 0.298 |

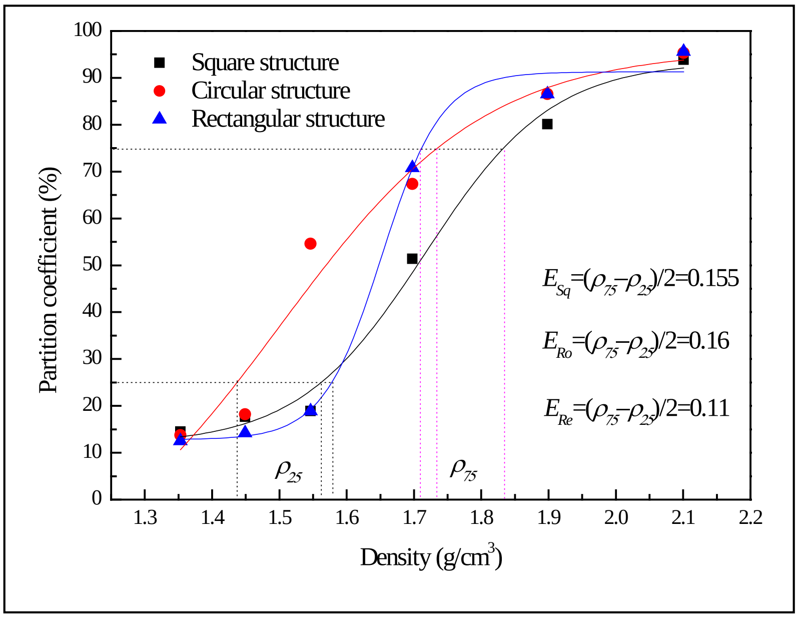


**Fig. 10.** Distribution curves of fluidized beds for different bed structures

Meanwhile, because of their similar height–diameter ratios, the square and circular fluidized beds exhibit similar back-mixing degrees of particles. As a result, the differences of their probable error $E_p$ values are not very great. This indicates that bed structure has no significant effect on the separation performance of fluidized beds with the similar height-diameter ratios.

## 4. Conclusions

(1) As bed heights increase, the density standard deviations of gas–solid fluidized beds with different bed structures increase, and bed stability decrease. For bed heights lower than 130 mm, the density fluctuations in the fluidized bed are relatively small. The density standard deviations for rectangular fluidized beds are obviously smaller than those of square and circular fluidized beds, indicating that the rectangular fluidized beds provide better fluidization environments.

(2) The addition of fine coal broadens the size fractions of medium particles, which improves fluidization quality and reduces the separation density of the bed. In particular, when the fine coal content is 10%, the bed exhibits the smallest density fluctuations ($S_p$ = 0.0714), producing more uniform densities and a suitable separation environment. Similar bed density trends are observed for the different bed structures as fine coal content increases, indicating that the influence of fine coal content on density distributions has little relation with bed structure.

(3) For a static bed height of 130 mm, fluidization number of 1.5, and fine coal content of 10%, the fluidized beds generally exhibit a higher ash stratification degree and better separation effects. The separation experiment results indicate that the probable error $E_p$ value for the rectangular fluidized beds is 0.11g/cm$^3$, which is smaller than that for the square (0.155g/cm$^3$) and circular (0.16g/cm$^3$) beds. Meanwhile, the height–diameter ratios of the circular and square fluidized beds are equal. Therefore, the back-mixing degree of the medium is similar and the $E_{\mathrm{p}}$ values are almost the same. The results show that bed structure does not significantly affect the separation performance of fluidized beds when their height–diameter ratios are the same.

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