Characteristics Analysis of the Blockage Zone in a Gas–Solid Fluidized Bed

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ABSTRACT: A gas–solid separation fluidized bed, which belongs to dry separation and can save a lot of water resources, is an important method for coal quality improvement. The effect of regional blockage of the air distributor on the fluidization effect was investigated by varying the blockage area and fluidization gas velocity, and the influence law of blockage of an air distributor on bed stability was revealed. In this paper, the micro-differential pressure sensor is used as a testing tool to analyze the regional characteristics of the fluidized bed blockage hole. The results show that when the air distributor is plugged, the standard deviations of the pressure fluctuation are largest at a height of 100 mm, all reaching more than 2.0, and that the pressure fluctuation at the bottom is greater than that at the top. When the plugged area fraction increases from 1/8 to 1/2, the density fluctuation range at the bottom of the plugged area decreases from 0.2 to 0.04 g/cm³, while the range of influence increases from 10 to 16 cm axially. With the increase of fluidization gas velocity, the mixing effect of particles is improved to an extent, and the range of the affected zone is gradually reduced.

1. INTRODUCTION

Owing to China’s status as the world’s largest developing country, coal is expected to remain its most important energy resource for the foreseeable future. The clean and efficient use of coal is therefore vital to China’s energy security, energy conservation, and environmental protection goals.1 Traditional coal separation processes are mainly based on wet separation techniques, which consume a lot of water2 and include the use of equipment such as cyclones, flotation machines, flotation columns, and jigs.3–5 The resulting product has higher moisture content after selection, which leads to a decrease in coal quality. In addition, the requirement for complicated slime water treatment in the separation process leads to certain limitations in wet coal preparation. Another drawback of these types of processes is that a considerable number of young coal types are easy to slime when exposed to water and are therefore unsuitable for wet separation. More than two-thirds of coal resources in China are distributed in arid areas such as Northwest and North China.6–8 Due to the shortage of water resources, the use of traditional wet separation technology is restricted, as large-scale wet separation equipment cannot be utilized. Against this backdrop, the development of dry separation techniques has generated considerable research interest.9,10 One such technique is gas–solid fluidized bed separation, which shows great promise as an efficient and clean coal separation technology. Due to the unique advantage of being water-free, the technique has a wide range of potential applications.11 Efficient dry separation technology can therefore make up for the shortcomings of coal separation technology in China and increase the proportion of coal selected in the country.

To date, there have been several promising research studies on the use of dry separation technology for coal separation and processing, and it has been gradually applied in large-scale industrial applications. Gas–solid fluidized bed separation, in which coal is stratified according to the bed density, has emerged as one of the more important separation processes.12 The quality of fluidization in the bed is heavily dependent on the air distribution device used,13,14 as without uniform stability of the bed density, the coal cannot be effectively separated. The main functions of the air distributor are to bear the particulate material in the fluidized bed such that the airflow is evenly distributed, and to act over the entire bed section to maintain the stability of the bed, ensuring continuous and efficient separation.15 In industrial processes, blockage of the air distributor occurs during operation, resulting in uneven particle mixing, unstable bed density, and low sorting efficiency, all of which adversely affect the
separation performance. To a large extent therefore, the performance of the air distributor determines the fluidization quality. To date, however, there are relatively few studies in the literature on the effect of the blockage area on the gas–solid separation fluidized bed performance.

The monitoring of gas–solid fluidized beds is usually done using the pressure fluctuation test method. The pressure signal is an important part of fluidization dynamics, as it is directly related to the gas distribution and fluidization state. Because dead zones caused by the plugged area of the distributor always exist, it is necessary to adopt a small-scale local detection method to separate the plugged area from the adjacent areas. Researchers in the field of fluidization use a variety of methods to analyze the pressure signal in the fluidized bed, including statistical analysis (time domain), frequency analysis (frequency domain), and nonlinear analysis (such as chaotic methods) techniques.

In this study, a statistical analysis method was used to investigate the influence of the blockage area and the fluidization gas velocity on bed fluidization and stability. The regional characteristics of the blockage holes were analyzed by using the micro-pressure differential sensor, and the fluidized state of the bed was represented by the bed density and the standard deviation of the bed pressure fluctuation.

2. EXPERIMENTAL STUDY

2.1. Test System. The experiments conducted in this study were performed on a laboratory-scale gas–solid fluidized bed. The experimental apparatus consisted of an air supply system, a separation system, and a test system, as illustrated in Figure 1. The air supply system, which provides a stable gas flow for the experiments, consisted of a Roots blower, a pressure tank, a flow meter, and an air flow switch. The separation system consisted of an air chamber, an air distributor, and a cylindrical gas–solid separation fluidized bed with a diameter of 30 cm in diameter and a height of 50 cm. To allow the fluidization state to be conveniently observed, the cavity of the fluidized bed was made from organic glass. Based on the traditional air distributor, the industrial double-layer filter cloth was used as the air distribution device to ensure the uniformity and stability of the air flow and promote the uniform fluidization of particles in the bed. The test system was used to measure the pressure fluctuations in the fluidized bed.

2.2. Pressure Sensor. To study the density and pressure of the bed, a pressure sensor which is more accurate than U-tube tests and can accurately measure pressure fluctuations over a period of time was used. The test system consisted of a micro-differential pressure sensor and NI acquisition card and LabVIEW pressure acquisition software. In this system, pressure fluctuations are transmitted to the micro-differential pressure sensor via the pressure measuring tube and converted into an electrical signal, which is then recorded by the NI acquisition card and processed using the LabVIEW software to obtain the pressure and density of the bed. One end of the piezometer tube is covered with nylon cloth to prevent fine-grained particles from entering, and the other end is connected to the pressure sensor. Prior to testing, a U-tube was used to calibrate the micro-differential pressure sensor by feeding in an airflow and recording the pressure change in the U-tube. This enabled the calibration curve for the relationship between the pressure and the electrical signal to be determined, which was used in subsequent experiments.

2.3. Materials. The particle size distribution of the medium particles is a key factor affecting the uniformity and stability of the bed density. If the distribution is too large, the final velocity of disturbed settling of coarse and fine particles is different, causing stratification and classification in the fluidized bed, which is not conducive to the formation of a uniform and stable bed. Therefore, the particle size distribution in the fluidized bed must be controlled to within a certain range.

In the experiments, the medium particles consisted of Geldart B magnetite powder, and the particle size range was mainly 0.074–0.3 mm. Geldart B magnetite powder not only has a suitable bulk density, but also can form a gas–solid suspension with a uniform and stable density under the action of compressed air, that is, its fluidization quality is high. The true density of the magnetite powder was measured to be 4600 kg/m³, and its bulk density was 2660 kg/m³. The magnetite powder was sieved using a vibrating screen, with the main particle size distribution ranges being 0.074–0.125 mm, 0.125–0.2 mm, and 0.2–0.3 mm, as shown in Figure 2.

These three size ranges accounted for 98.6% of the total particle mass and the remainder of the particles accounted for 1.4%. Therefore, this study mainly used the dominant particle size as medium particles of the fluidized bed. In addition, as the magnetite powder has strong magnetic properties, a magnetic separator can be used to efficiently recover it for recycling afterward.

2.4. Characterization Methods. 2.4.1. Standard Deviation. The standard deviation of bed pressure fluctuation was used to reflect the stability of the bed density, which in turn reflects the fluidization state of the bed:
Figure 3. Comparison chart of standard deviation of bed pressure fluctuation and density.

\[
\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (P_i - \bar{P})^2}
\]  

(1)

where \(\sigma\) represents the standard deviation of the bed pressure fluctuation, \(P_i\) represents the bed pressure at the \(i\)th measurement point; \(\bar{P}\) represents the average value of the bed pressure at each measurement point, and \(N\) is the total number of measurement points. When \(\sigma\) is small, the pressure fluctuations of the fluidized bed are small, meaning that the density of the bed is stable and the fluidization effect is good.

2.4.2. Average Bed Density. The average density of the bed may be calculated as a function of pressure as follows:

\[
\bar{\rho} = \frac{\Delta P}{gH}
\]  

(2)

where \(\bar{\rho}\) is the average density of the bed, \(\Delta P\) is the pressure, and \(H\) is the height difference of the pressure measuring point.

3. RESULTS AND DISCUSSION

3.1. Influence of Air Distributor Blockage on Bed Stability. The air distributor was divided into six equal parts, labeled as A–F, as shown in Figure 4. In order to study the density and pressure fluctuation at different bed heights when the air distributor is plugged, area A was set as the plugged region, with the remaining areas in the unplugged state. This experiment took four areas A, B, C, and D as the research objects and used the standard deviation of pressure fluctuations and the bed density to reflect the fluidization state of the bed. In the gas–solid fluidized bed, the key factor affecting the separation efficiency is the uniformity of the density distribution of the bed. In particular, the axial density distribution limits the effective separation of minerals. In this experiment, the heights of the test points from the air distributor were set at 40, 100, 160, and 220 mm.

In the experiments, the fluidization velocity was fixed at 1.25U_{mf} (where U_{mf} is the minimum fluidization velocity). As shown in Figure 3, when the air distributor was not plugged, the corresponding standard deviations of the pressure fluctuation at each test point in area A were 1.578, 1.997, 1.438, and 1.248, respectively. At this point, the density distribution in the fluidized bed was uniform and the fluidization effect was good. When area A was plugged, the fluidization effect in this region worsened significantly, with standard deviations of 1.794, 2.403, 1.671, and 1.388, respectively, and a part of the regions B and F were also affected. The standard deviations of pressure fluctuation in all four test points increased, with the greatest increase being at the 100 mm test point. The areas A, B, C, and D have the same properties. Pressure fluctuations are mainly caused by the bubble movement and particle accumulation in the plugged area. When the fluidization gas velocity is fixed, the presence of the plugged area results in uneven air distribution in the bed, and the accumulation of particles results in larger bubbles being formed. At a height of about 100 mm, some mixing occurs between the bubbles in the normal area and the
particles in the plugged area, which causes the particle movement to intensify, increasing the standard deviation of the pressure fluctuation of the bed.

Figure 3 shows that when the air distributor is plugged, the standard deviation of the pressure fluctuation in all areas increases significantly, with region B being most affected. In addition, the standard deviations of the pressure fluctuation in all four regions increase along the axial direction to reach the maximum at first and then decreases gradually. As the bubbles reach the surface of the bed and break, the pressure fluctuation at the top of the bed will be more uniform, causing the standard deviation of the pressure fluctuation at the top of the bed to be significantly lower than that at the bottom. When the air distributor is plugged, larger bubbles can be clearly observed at the edge of the plugged area, causing significant lateral movement of particles in the plugged area, as well as in regions B and F. This improved mixing of the particles at the bottom of the bed causes the pressure of the bed to fluctuate greatly, which affects the fluidization performance.

According to the abovementioned research, when the air distributor is plugged, the standard deviation of bed pressure fluctuation at 100 mm is the largest. Areas A−D were selected as the test areas, and the pressure was measured at a height of 100 mm from the bottom of the bed, with the fluidization gas velocity fixed at 1.2U_{mf}. The pressure change of the fluidized bed was measured using the micro-differential pressure sensor with a collection time of 5 s (select 2−4 s data) and a collection frequency of 1000 Hz.

Figure 4 shows the fluctuation of bed density before and after the blockage of the air distributor. The density distribution of the overall bed is relatively uniform with time for the unplugged air distributor, indicating good bed stability. When region A is plugged, the density distribution in the A area of the bed is extremely uneven, and the fluctuation of the bed density fluctuates sharply. Its average density decreases from 2.15 to 2.0 g/cm³ due to the decrease of the bottom airflow into the pressure measuring tube. The plugged area also causes the densities of regions B, C, and D to increase to different extents, with the largest increase occurring in region B. Due to the lateral movement of bubbles, the bed density in region B fluctuates violently and is in an extremely unstable state. As regions C and D are relatively further away from region A, they are less affected by it and show less bed density fluctuations.

3.2. Effect of Fluidization Gas Velocity on Bed Stability. Here, the bed instability caused by the blockage of the air distributor at different fluidization gas velocities was investigated. The plugged area fraction of the air distributor was fixed at 1/6, and fluidization gas velocity values of 1.1U_{mf}, 1.3U_{mf}, 1.5U_{mf} and 1.7U_{mf} were used.

When the air distributor is plugged, increasing the fluidization gas velocity significantly improves the fluidization effect in the bed. At the bottom of the fluidized bed, there is no air supply to the plugged area; hence, the density of particles accumulated above this area will increase, causing the particles to tend to spread to the unaffected parts of the bed. This generates resistance to the bubbles near the plugged area, causing the bubbles to move away from this area, as shown in Figure 5. In the upper part of the fluidized bed, the particle resistance of the bubbles becomes smaller, and some of the bubbles diffuse in the direction of the plugged area, thereby reducing the influence of this area on the upper part of the fluidized bed. In these experiments, the density distribution of the bed at heights of 10, 40, 70, and 110 mm from the air distributor was tested, as shown in Figure 6.

As can be seen from Figure 6, the affected area has a broadly symmetrical nature. With area A as the center, the affected areas are roughly the same on both sides. The further the bed is from the air distributor, the smaller the area of the bed that will be affected. As the fluidization gas velocity increases, the overall density of the bed gradually decreases and then stabilizes, and the area of the bed affected by blockage is gradually reduced. This is because as the fluidization gas velocity increases, the rate of bubble generation in the normal zone increases, the expansion of the bed increases, the porosity of the bed increases, and so do the diameter of the bubbles and the rate of bubble rise. This increases the contact area between the air bubbles in the normal area and the particles above the
plugged area, thereby increasing the movement of particles and causing them to gradually mix evenly with the particles in the unplugged area. This helps to improve the mixing effect of the particles in the bed to an extent, so that the particles accumulated above the plugged area are gradually reduced, and the size of the affected area in the bed is gradually reduced. However, due to the limited bubble diffusion ability in the normal area, some particles will still accumulate in the plugged area, worsening the overall fluidization of the bed.

3.3. Effect of the Blockage Area on Bed Stability. The blockage area is an important factor that affects the regional characteristics of the air distributor. Here, the effect on the bed density of having blockage area fractions of 1/8, 1/6, 1/4, and 1/2 of the total air distributor area on the bed stability was investigated, at a fixed fluidization gas velocity of 1.25\(U_{mf}\).

Figure 6. Schematic diagram of the influence range of different fluidizing gas velocities.
Figure 7 shows the density fluctuations near the air distributor at the center of the blockage area for different blockage fractions. With the gradual increase in the size of the plugged area, the density fluctuations of this area gradually become smaller. When the plugged area fraction is $1/8$, the density fluctuation is extremely severe, with a fluctuation range of about $0.2 \text{ g/cm}^3$. When the plugged area fractions are $1/6$ and $1/4$, the density fluctuations are significantly smaller, with ranges of $0.12$ and $0.10 \text{ g/cm}^3$, respectively. When the plugged area fraction is $1/2$, the density fluctuation in this area is extremely small, with a fluctuation range of only $\sim 0.04 \text{ g/cm}^3$.

When the air distributor is plugged, the fluidized bed cannot supply airflow to the plugged area. Above the distributor, some particles accumulate in their starting positions (which is referred to as a particle dead zone). These particles can only rely on the diffusion of air bubbles in the unaffected parts of the bed to help them mix with other particles. However, as the plugged area increases, the bubble diffusion capacity in the unaffected parts of the bed is gradually limited, causing more and more particles to accumulate above the plugged area, which reduces both the porosity and the density fluctuation of the bed. When the blockage area fraction of the air distributor reaches $1/2$, the accumulation of particles in the blockage area is the greatest, and the fluidization in the bed is extremely unstable.

Figure 8 shows that as the plugged area increases, the influence height of the plugged area in the longitudinal direction also varies. When the blockage area fraction is $1/8$, the longitudinal influence height is $10 \text{ cm}$. When the blockage area fractions are $1/6$ and $1/4$, the influence heights in the longitudinal direction are relatively close, both being $\sim 13 \text{ cm}$. When the blockage area fraction reaches $1/2$, the longitudinal influence height is $16 \text{ cm}$. This shows that as the blockage area fraction increases, the volume of the bed affected by it gradually increases. When the air distributor is plugged, the density of the measured points is significantly lower in some areas. This is due to the lack of air supply in the plugged area, making it difficult for airflow to enter the measuring tube, thereby resulting in the measured density value in this area being understated. This is especially true at the bottom of the blockage area, where the accumulation of particles is greatest and the porosity of the bed layer is at its lowest.

The experimental results indicate that blockage of part of the air distributor will cause severe fluctuations in the density of the fluidized bed. The effect of the plugged area on the bed is approximately symmetrical. In production practice, through the analysis of sensor test data, the location and area of air distributor blockage can be roughly obtained, and the air distributor failure can be repaired in time. The micro-pressure
It also increases. Method to monitor blockage in the fluidized bed area. Decreased gradually along the axial direction. The pressure of the fluidized bed area decreased from 0.20 to 0.04 g/cm³, and the blockage of the area fraction has a broadly symmetrical nature. As the blockage area fraction of the distributor increased from 1/8 to 1/2, the density fluctuation range at the bottom of the plugged area decreased from 0.20 to 0.04 g/cm³, and the influence height in the longitudinal direction gradually increased from 100 to 160 mm. This indicates that with the increase of the plugged area, the volume of the bed affected by it also increases.

4. CONCLUSIONS

This paper studied the effect of regional blockage of the air distributor on the fluidization effect by varying the blockage area and fluidization gas velocity and revealed the influence law of blockage of the air distributor on bed stability. The main conclusions of this study are as follows:

1. After the air distributor was plugged, the pressure fluctuation was the most severe at a height of 100 mm from the distributor. The standard deviations of pressure fluctuation for each region increased to the maximum value and then decreased gradually along the axial direction. The pressure fluctuation at the bottom of the bed was significantly higher than that at the top.

2. When the blockage area fraction is fixed, the zone affected by the blockage area gradually becomes smaller. The farther the bed is from the air distributor, the smaller the affected area is. In the fluidized bed, the affected area has a broadly symmetrical nature.

3. As the blockage area fraction of the distributor increased from 1/8 to 1/2, the density fluctuation range at the bottom of the plugged area decreased from 0.20 to 0.04 g/cm³.

4. The use of micro-differential pressure sensors to analyze the fluctuation of bed density and pressure can be used as a method to monitor blockage in the fluidized bed area.

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