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Particle mixing and separation performance of gas-solid separation fluidized beds containing binary mixtures

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ABSTRACT

In the separation process on a gas-solid separation fluidized bed, formation of binary mixtures of fine coal and magnetite is inevitable. Using a high-speed camera system (HSCS), the formation of these binary mixtures was observed, and the mixing mechanism was established. The effects of different factors (e.g. gas velocity and size fraction and mixture ratio of fine coal) on the degree of mixing of binary mixture particles were studied using a combination of factor analysis method and orthogonal test method. The results show that the mixing process of fine coal and magnetite plays a crucial role in the adjustment of the bed density. It is clear that the bed density can maintain their identities only when the fine coal and the magnetite are fully mixed. The degree of mixing of binary particles increased with increasing gas velocity while the value decreased with increasing size fraction and mixing ratio of fine coal. The three factors influencing the mixing efficiency showed the following order as: gas velocity, mixture ratio and size fraction of fine coal. Maximum degree of mixing was obtained for the gas velocity of 9.83 cm/s, particle sizes less than 0.15 mm and mixing ratio of 5%. According to the sorting test, the separation efficiency of the gas-solid separation fluidized bed containing binary mixtures is more obvious under the optimal working conditions, i.e., clean coal is obtained with the ash content reduced by 25.67% compared with raw coal and the probable error (E) is 0.13.

1. Introduction

Currently, China's energy supply is heavily reliant on coal, and this status will last for decades to come. However, the environmental pollution and energy waste associated with coal combustion has hindered the development of the coal industry. Therefore, the cleaning utilization of coal is a major technique to solve the abovementioned problems. The traditional wet beneficiation processes have good separation efficiencies as coal cleaning technology; however, it is easy to make the waste that pollute water resources. Moreover, in northwest China, the technology of wet separation is difficult to be popularized due to lack of water resources. In contrast, the developing dry beneficiation processes does not use water and have many advantages including no addition of moisture to the products and no emission of slime water to the environment. Among these processes, the gas-solid separation fluidized bed uses a two-phase gas-solid flow as the separation medium, and effectively separates raw coal under dry conditions, which is an indispensable mainstream in dry separation technology [1–3].

In the gas-solid separation fluidized bed, magnetite is used as the medium particle. Its relatively narrow size fraction suggests that the fluidized bed is composed of single component particles. However, in the actual separation process, the raw coal, especially fine coal, destroys the single-component properties of the fluidized bed. Due to the continuity of sorting, although the lump coal is discharged after sorting, the fine coal remains in the bed and is not discharged effectively. Sometimes, to regulate the separation density of the fluidized bed, the fine coal is added to the fluidized bed artificially[4–6]. Therefore, the fluidized bed layer is composed of binary mixtures comprising fine coal and magnetite, formed during the actual separation process. Thus, the study of the mixing mechanism of fine coal and magnetite is of great significance for controlling the density stability of the fluidized bed and for ensuring good separation performance.

Several experiments and theoretical analyses have been performed on particle mixing in gas-solid fluidized bed. In the early stages, the gas-solid fluidized bed was regarded as an ideal system consisting of particles of the same density and size. Therefore, the influence of bed material on the mixing behavior was ignored, and the research was mainly focused on the particle mixing mechanism. Earlier studies by Rowe et al. [7,8] showed that particle mixing was caused by gas bubbles. With increasing gas velocity, the action of gas bubbles intensified

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and particle mixing became more severe. Based on this, other researchers performed more detailed studies, such as Stephens et al. [9], Bridgwater et al. [10], Litka et al. [11], Morooka et al. [12], Luo et al. [13]. They hypothesized the mixing mechanism of the particles as follows: when the bubble rises, the tail vortex of the bubble entrains some particles. As the bubble rises to a certain height, these entrained particles fall off due to their own weight, while the surrounding particles drop to the space vacated by the rising bubbles. Such spatial movement of the particles is called backmixing. However, in the practical application of the fluidized bed, the ideal single-component particle system is rare. In fact, the gas-solid fluidized bed is a multi-component particle mixing system. Therefore, follow-up research involved studying the mixing mechanism of multi-component particles in the gas-solid fluidized bed. Rice and Brainovich [14] studied the effects of size differences for equal-density particles in binary mixtures. A similar study was also performed by Goldschmidt et al. [15]. Recently, Fotovat et al. [16] used the radioactive particle tracking method to analyze wood distribution in a sand fluidized bed, and found wood distribution all along the bed and better gas mixing with increasing gas velocity. There have been extensive research on the mixing behavior of multicomponent particles by other researchers (Massol-Chaudeur et al. [17]; Lu et al. [18]; Feng et al. [19]; Hogg et al. [20]; Olaofe et al. [21]), who have proposed the following basic mixing mechanism for multicomponent particles in the gas-solid fluidized bed: For binary particles, the mixing process is divided into three types of mixing: convective mixing, which involves the collective transfer of groups of particles from one location to another, diffusive mixing, defined as the distribution of particles over a freshly developed surface, and shear mixing due to slipping planes set up within the mixture. Furthermore, the mixture of multi component particles is composed by a plurality of binary components particles mixing.

The abovementioned research has mainly focused on the highly sought-after applications of fluidized bed in the fields of medicine, biology, food, and chemical industry. However, the mixing of multi-component particles in the gas-solid separation fluidized bed during mineral processing is seldom reported, especially the formation of binary particles composed of fine coal and magnetite. This paper discusses the mixing mechanism of binary particles (comprising pulverized coal and magnetite) in a gas-solid separation fluidized bed by systematically studying the factors influencing the formation of binary particles under different working conditions. This provides a valid theoretical basis for density regulation and effective separation on a gas-solid separation fluidized bed.

2. Experimental

2.1. Experimental system and method

The test facility (Fig. 1) consisted of a model rectangular fluidized bed (160 mm (L) × 160 mm (W) × 400 mm (H)) made of Perspex and equipped with an air chamber, an air distribution plate, a bed body, a U-type pressure gauge to measure the pressure drop in the bed, and a high-speed camera system (HSCS) to capture the mixing state of the binary particles in the fluidized bed under different operating conditions.

To elucidate the mixing mechanism of the binary mixture (magnetite and fine coal) in the gas-solid separation fluidized bed, the components are placed separately in a certain mixing ratio (5%, 10%, or 15% of fine coal) to form the initial bed with the coal layer on top. The weight of the magnetite is fixed at 4 kg to fit the bed size, and the weight of fine coal is adjusted according to the mixing ratio. During the measurement, the initial bed is fluidized for 5 min at the set gas velocity, and the fluidized bed collapses to the static bed after the valve is closed suddenly. The static bed is evenly divided into five layers according to bed height; after magnetic separation, the component particles of each layer are distinguished to calculate the mixing index. To study the effect of fine coal on the degree of mixing, the fine coal should be divided into three fractions: fine fraction (0–0.15 mm), medium fraction (0.15–0.3 mm) and coarse fraction (0.3–0.6 mm).

2.2. Material

The properties of magnetite and fine coal, the components of the binary particles studied in gas-solid separation fluidized bed are shown in Table 1.

2.3. Evaluation

In the binary particle mixing system, it is believed that the large or heavy particles settle in the lower part of the bed, called the deposition component; while the small or light particles float to the top of the bed, called the floating component [22]. For a two-component fluidized bed, magnetite can be considered the deposition component due to its high density, while pulverized coal should be considered the floating component due to its lower density. The degree of mixing of the two components can be determined by the row mixing index [22].

$$M = \frac{X}{\overline{X}} \tag{1}$$

where X is the mass fraction of the deposition component (%); and $\overline{X}$ is the average fraction of the deposition component in the whole bed (%).

In an actual fluidized bed, magnetite is the dominant component. The difference between X and $\overline{X}$ values measured by the test is small, and the stratification of the upper and lower beds is vague. The row mixing index cannot effectively represent the degree of mixing of the binary mixtures in the gas-solid separation fluidized bed. Since the content of the floating component (fine coal) in each layer can be measured, the standard deviation of the distribution of this component along the axial direction can be calculated using data statistics, as follow:

$$S = \sqrt{\frac{\lim_{i\to n}(c_i - \overline{c})^2}{n-1}} \tag{2}$$

where c_i is the content of the floating component in layer i (%); $\overline{c}$ is the average content of the floating component (%) in the entire bed; and n is the number of samples (in this study, $n = 5$).

Thus, S can be used as an index for the degree of mixing of binary mixtures in the fluidized bed; the smaller the value of S, the better is the degree of mixing. When , it indicates that the two components of the binary particles have been completely mixed in the fluidized bed.

3. Mixed mechanism

The mixing kinetics of binary mixtures in the fluidized bed can be obtained by measuring (or estimating) the standard deviation (σ^2) (Eq. (3)) of the mixture composition with various mixing times [17].

$$\sigma^2 = \frac{p(1-p)}{n} \tag{3}$$

where n is the total number of component particles in the sample and p is the number percentage of single-component particles (%).

The typical binary mixture curve, i.e. the standard deviation curve, is an approximately exponential curve obtained based on the results of a large number of experiments (Fig. 2) [18]. The early stages of rapid reduction indicate that the degree of mixing of the binary components increased rapidly, mainly due to convective mixing of the components under the convective and shear forces. Therefore, this stage is considered as the macro-mixing stage. The latter stage is a gradual floating stage, where the curve fluctuates around a certain value. In this stage, the individual particles of each component begin to diffuse and mix under the actions of gravity and interparticle interaction force, i.e. this