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Kinematic properties and beneficiation performance of fine coal in a continuous vibrated gas-fluidized bed separator

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HIGHLIGHTS

- A continuous vibrated gas-fluidized bed separator was designed and established.
- Kinematic properties of fine coal particles in a continuous separator were investigated.
- Models of average conveying velocity and bed height distribution were proposed.
- The beneficiation performance was evaluated and the E value was 0.225.

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ABSTRACT

Dry beneficiation of fine coal is increasingly significant for the clean utilization of coal resources in drought regions. In this paper, a continuous vibrated gas-fluidized bed separator was developed for fine coal dry beneficiation. The fluidization behavior and the kinematic properties of fine coal particles in this separator were systematically investigated. The results show that the bed expansion increases linearly with the superficial air velocity and theoretically, higher bed expansion benefits the hindered settling process of fine coal particles. However, larger superficial air velocity will induce intense fluctuation in bed surface. The conveying velocity of particles is mainly determined by the vibration angle and a predicted model is established by the nonlinear regression analysis. The kinematic properties underlying the particles diffusion in the separator are theoretically analyzed and a theoretical model of bed height distribution is established and this model fits the measured value well. The beneficiation performance of this separator is also evaluated by separating $-3+1$ mm fine coal. The results show that the probable error, E, is 0.225, indicating a continuous vibrated gas-fluidized bed separator can achieve a satisfactory performance.

1. Introduction

In 2014, China's coal production was up to 3.87 billion tons, accounting for 76.7% of China's primary energy production. China's energy supply is highly reliant on coal and consequently, China is suffering from serious environmental pollution mainly due to the increasing emissions such as SO_x, NO_x and dust [1,2]. China has introduced policies to promote the sustainable development of the coal sector. In the "Air Pollution Prevention and Control Action Plan" issued in September 2013, China has set a goal of increasing the run-of-mine coal to preparation ratio to more than 70% by 2017. However the recent ratio is just 56.2%, it will be, therefore, a big challenge to achieve this goal and a great effort should be made to develop advanced coal beneficiation technologies.

Coal beneficiation is generally classified into wet and dry processes. Recently, wet processes have better separation accuracy and are dominant in the global sector of coal processing. However, wet processes need a large amount of water and consequently are difficult to be employed in the regions with limited water accessibility. This situation is especially serious in China. More than 65% of China's coal resources reserves in Northwest China and these regions are generally drought. Thus, China is urgent to develop dry processes. Similarly, other countries such as South Africa, Turkey, India, Canada, Brazil and Australia are all engaged in the research and development of dry processes of coal beneficiation.

Recent literature on dry processes mainly focused on coarse coal (+6 mm) beneficiation. The representative processes, such as

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air dense medium fluidized bed separation (ADMFB) [3–5], air jigging [6–8] and compound dry separation [9,10], have been sufficiently investigated both in laboratory studies and in industrial applications. Recently, fine coal dry beneficiation has been gaining more and more academic interest [11]. Studies reported by Luo et al. [12] and Macpherson et al. [13,14] introduced vibration energy into ADMFBs to separate fine coal and showed that the probable error *E*, was 0.07–0.23. Song et al. [15] introduced a magnetic field into an ADMFB for −6 + 0.5 mm fine coal beneficiation and the corresponding *E* value was 0.75–0.85. Dong et al. [16] introduced an additional pulsing air flow into an ADMFB to separate −6 + 3 mm fine coal and the corresponding *E* values of high and low density separation were 0.190 and 0.245, respectively. There were also several studies [17–19] that attempted to use a conventional ADMFB to separate low-quality fine coal by making several modifications to its operational factors, including a smaller bed height and a finer dense medium. However, these processes mentioned above all use an additional dense medium like magnetite powder or sand and consequently, it is very difficult to obtain a satisfactory performance in the stages of product purification and dense medium recovery recently.

In this paper, we developed a continuous vibrated gas-fluidized bed separator (hereinafter referred as a continuous separator) for fine coal dry beneficiation. This continuous separator used no dense medium and separates fine coal based on density segregation. Hence the problems of product purification and dense medium recovery were no longer an issue. The kinematic properties of fine coal particles in a continuous separator were systematically investigated. Furthermore, the beneficiation performance of a continuous separator was experimentally evaluated.

2. Separation mechanism

Heterogeneous particles under fluidization tend to segregate by size/density [20]. When a fluidized bed is used to separate fine coal, more effort should be made to strengthen the density segregation and weaken the size segregation. Thus, in this study, −3 + 1 mm fine coal particles with a narrow size range was used, aiming to reduce the effect of size segregation on separation performance.

The −3 + 1 mm fine coal investigated belongs to Geldart D particles [21] and these particles are very prone to commence channeling and large bubbles in a conventional gas-fluidized bed, leading to a poor performance of density segregation. Therefore, vibration energy is introduced to eliminate the channeling and improve fluidization quality. A fluidized bed of fine coal under the collaborative function of air flow and vibration has a large bed expansion and gentle bubbling behavior. Fine coal particles conduct hindered settling processes under the gravity force and air drag force. Gangue particles with higher density have bigger settling acceleration than clean coal particles with lower density. Thus, gangue particles settle faster and arrive at the bottom of the bed. Finally, particles in the upper section of the bed are collected as a clean coal product, particles in the lower section as a gangue product and particles in the middle section as a middling product if required.

3. Materials and experimental

3.1. Properties of fine coal investigated

Wuhai region located in Northwest China has abundant coal resources. This region is drought and urgently needs dry processes of coal beneficiation. Fine coal having a size fraction of −3 + 1 mm derived from a Wuhai opencast coal mine is experimentally investigated in this paper and its density distribution is given in Table 1.

3.2. Equipment structure

A continuous vibrated gas-fluidized bed separator was designed and established in China University of Mining and Technology, as shown in Fig. 1. It consists of four main parts: a feeding part including a feed silo and an impeller feeder, a fluidized bed part including a separating bed, an air distributor and an air chamber, a vibration part including two vibration motors and their controlling devices and a product discharging part including three impeller discharging devices and an overflow collector. The effective size of the separating bed is 400 mm in width and 1830 mm in length. The impeller feeder and the separating bed are connected by the flexible materials to prevent the feed silo and the impeller feeder from participating in vibration. Two vibration motors are symmetrically mounted on both sides of the separator in order to achieve synchronization and provide linear vibration excitation. Three impeller discharging devices are installed at the bottom of the separator.

3.3. Processing procedures

In this study, the first two impeller discharging devices are closed and the last one is opened to discharge gangue particles. Clean coal particles are discharged by overflow. Fine coal particles enter the separating bed with a fixed feeding velocity which is adjusted by an impeller feeder. These particles are fluidized under the combined function of fluidizing air and the vertical component of vibration and then conduct the hindered settling processes. Meanwhile, the particles bed moves forward due to the horizontal component of vibration and particles diffusion. After a certain time, the particles bed achieves a stable performance of density segregation and then particles in the lower section of the bed are discharged as a gangue product, meanwhile, particles in the upper section are discharged as a clean coal product. The dust produced during the separation process is collected by a fabric filter.

4. Results and discussion

4.1. Fluidization behavior of a continuous separator

In this paper, the vibrational parameters of a continuous separator are selected according to the batch separation results reported in our previous paper [22]. The vibrational frequency is 21 Hz and the vibrational amplitude is 2 mm. Under this condition, the minimum fluidization velocity of particles bed is 0.46 m/s and the bed height at the minimum fluidization is 70 mm.

When the superficial air velocity (U) increases beyond the minimum fluidization velocity (U_{mf}), the bed expands increasingly. In this study, the expansion behavior is evaluated by measuring the expansion ratio, $\varepsilon = H/H_0$, where H is the average bed height at U and H_0 is the average bed height at U_{mf}. The bed expansion behavior is depicted in Fig. 2(a). It can be seen that the expansion ratio approximately increases linearly with U. According to the separation mechanism, a larger bed expansion ratio is favorable for density segregation of fine coal and it makes the bed has a lower solid concentration. Thus, the particles become loose enough and easily conduct the hindered settling processes, leading to a good performance of density segregation. However, the superficial air velocity can't increase too large to obtain a big expansion ratio. The big bubbles formed at larger U induce serious solid back mixing during their rising through the particles bed and intense fluctuation of bed surface when their eruptions on the surface. For a continuous separator, when the U increases to 0.56, many big bubbles commence