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Collaborative optimization of vibration and gas flow on fluidization quality and fine coal segregation in a vibrated dense medium fluidized bed

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ABSTRACT

In a vibrated dense medium fluidized bed (VDMFB), the uniform and stable gas-solid fluidized bed where medium particles belong to the Geldart B, was formed and considered suitable for 1–6 mm fine coal separation under the combined effects of both vibration energy and air flow. Driven by the excitation force, the particles in the VDMFB had a higher kinetic activity and lower minimum fluidization gas velocity. Prior to the bed fluidizing initiation (fluidization number, $N < 1$), the solid particles absorbed energy during inelastic collisions with the gas distributor. Subsequently to the bed uniform fluidization, the vibration energy was continuously transferred to the quasi-elastic bed in the form of waves. The vibration amplitude and frequency played a different role in the gas-solid contact. When the operating gas velocity, U_i, was 6.26 cm/s and the vibration acceleration level, K, was lower than 7.1, it could have been quite effective for the vibration energy transfer in the bed to be enhanced by the vibration frequency increase. As the frequency increased, the transmission efficiency of vibration energy decreased. When $K > 7.1$, the vibration amplitude effect on the vibration energy transmission in the bed was quite significant. In the study of the vibration energy effective range, it was discovered that the bed could be utilized for the fine coal effective separation in the area below 60 mm for the VDMFB with 80 mm of static bed height, where the vibration energy was continuously and steadily transmitted and attenuated along the bed height. Regarding the raw coal with a washability variety, the separation density could be flexibly regulated in the VDMFB. The separation results demonstrated that the ash content of three clean coal products was decreased exceeding 50%, compared to the ash content of the raw coal when the separation density was set at 1.49 g/cm^3, 1.67 g/cm^3 and 1.78 g/cm^3 respectively, indicating that the VDMFB could effectively separate fine coal by a dry method.

1. Introduction

The global coal consumption was 3.84 billion tons of oil equivalent in 2015, accounting for 29.2% of the world's primary energy consumption [1]. In addition to coal being utilized as a fuel for heat and kinetic energy, it can also be utilized in metallurgical coke, synthetic oil and thousands of chemical products production. Besides, the coal direct utilization has caused severe environmental pollution. The clean coal is a collection of technologies being developed in the environmental impact mitigation of coal utilization. It could lead in the removal of most sulfide minerals, silicide and other harmful substances in raw coal [2]. The carbon content and calorific value of the coal beneficiated increase highly, which not only contributes the coal utilization efficiency improvement in power generation, metallurgy and other industrial production processes, whereas also reduces the emission of SO_2, NO_x and other harmful gases highly [3,4]. Simultaneously, in clean coal technology the consumption of traffic capacity caused by the gangue and other useless components in raw coal can be avoided. Currently, wet coal separation technologies dominate the global scene among coal separation technologies. It is undeniable that wet coal separation technologies such as jigging [5], cyclone [6], flotation [7], allflux separator [8], etc. can achieve high separation efficiency. However, water supply difficulties will restrict the application of wet coal separation technologies in some areas where are dry or cold. Moreover, for the coal which is easily slimed, such as lignite, it is difficult to achieve ideal results by wet separation. For these cases, dry coal separation technology is more suitable than wet separation technology. In addition, compared to the wet coal separation system, dry separation system is more simple and will not produce coal slime water to pollute environment. In recent years, several dry coal beneficiation technologies for coarse-grained coal, including compound dry separator [9], air tables [10,11], air jigs [12] and gas-solid dense phase fluidized beds [13–15] have been successively developed. With the popularization of fully mechanized coal mining technology [16,17], the content of fine coal (−6 mm) in raw coal has been increasing,

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exceeding 50%. It has caused a serious waste of resources and environmental pollution that massively utilize low-quality fine coal without being beneficiated. In addition, coal resources and water resources in many parts of the world exist in reverse distribution [18–20]. For example, in China, two-thirds of the coal is distributed in the western region, where the total water resources only account for <10% of the total water resources in China. These realities indicate that the research and application requirements of fine coal dry separation technology are proven urgent and significant.

A gas-solid dense phase fluidized bed (GDPFB), with the Geldart B [21] magnetic powder as a heavy medium, has been effectively applied in lump coal beneficiation due to the corresponding wide adjustable range of separation density [22,23]. The probable error, E, value of products is 0.05–0.07 g/cm^3, which is improved than the other coal dry separation equipment. Besides, due to the low differences between the fine coal and the heavy medium particles sizes, the particle-group shielding effect caused by the back-mixing of the heavy medium particles under the action of bubbles led the fine coal to move synchronously along with the heavy medium particles, weakening the effect of beneficiation by bed density for fine coal [24]. Therefore, it was proven difficult for the fine coal within a GDPFB to be efficiently segregated.

Many scholars introduced the vibration into the ordinary fluidized bed and attempted to form a uniform and stable fluidized state by increasing particle motion activity and enhancing gas-solid contact. In the early days, Bratu and Ryzhkov et al. [25,26] studied the vibration behavior and basic fluidization characteristics of the vibrated fluidized bed. In recent years, Macpherson and Galvin [27] developed a vibrated reflux classifier, with silica sand as the heavy medium. 4–6.35 mm, 2–4 mm and 1–2 mm fine coal grains were separated with a probable error, E, with a value of 0.07 g/cm^3, 0.13 g/cm^3 and 0.23 g/cm^3, respectively. Dening Jia and Océane Cathary [28] replaced the continuous flow of the vibrated fluidized bed with the pulsating airflow, discovering that the retarded bubbles increased the gas hold-up and subsequently enhanced the heat and mass transfer rates. Barletta et al. [29] captured and analyzed the motion of the particles on the bed surface by high-speed cameras, calculating the theoretical values of both amplitude ratio and phase lag. Wang et al. [30] investigated the propagation of pressure waves in the vibrated fluidized bed. It was reported that the vibration energy was mainly consumed in the bed, whereas the wave velocity of the pressure wave ranged from 9 to 75 m/s. Luo et al. [31,32] introduced the vibration energy into a GDPFB to form quasi particulate fluidization conditions and 0.5–6 mm fine coal grains were effectively segregated, demonstrating that the probable error, E, was 0.07–0.23 g/cm^3. Liu [33] and Jin [34] analyzed the mechanical dynamics of a trough-shaped vibrated fluidized bed and deduced theoretically the total separation rate constant of the concentrates and tailings under steady conditions. Yang [35,36] designed and built a continuous autogenous medium vibrated fluidized bed separator, by a 0–6 mm refractory fine coal separation by the probable error, E, with a value of 0.175–0.225 g/cm^3.

The present work was focused on the flow regime of vibration fluidization and the related physical and structural parameters. The synergetic effect of vibration energy and airflow on the fluidization quality improvement of the vibrated dense medium fluidized bed (VDMFB) was lower. With consideration to the motion variance between the particle system and the vibrated bed, the synergetic effect mechanism of the vibration, the air on the medium particles and the optimization of the separation behavior were studied in this paper.

2. Experimental section

2.1. Apparatus

A schematic diagram of a VDMFB system is illustrated in Fig. 1. It mainly includes a gas supply system, a separator and a data acquisition and processing system. Blower (No. 1), buffer tank (No. 2) and electromagnetic valve (No. 3) compose of gas supply system, providing uniform and stable airflow for the VDMFB system. Operating gas velocity is controlled within the range of 0–20 cm/s by an electromagnetic valve. The VDMFB separator consists of a pre-gas distribution chamber (No. 6), a gas distributor (No. 7), a separation chamber (No. 8) and a shaker (No. 4) with a controller (No. 5). The vibration amplitude and frequency are adjusted by the RC-2000 digital vibration controller to provide exciting force for the VDMFB. The shaker is able to produce a sinusoidal vertical movement in the range of 0.1 to 100 Hz with displacement amplitudes of up to 10 mm. The gas distributor is rigidly connected with the shaker and moves synchronously. Pre-gas distribution chamber and gas distributor make rising gas distribute uniform and go into the fluidized separation chamber which is a vertical cylinder with an inner diameter of 120 mm and a vertical height of 400 mm, made from transparent organic glass. Different functions of sensors were used to collect the experimental data in real time. Differential pressure sensor which has the function of collecting the pressure signal of bed. Two copper tubes (No. 10) with an inner diameter of 2 mm are glued side by side and placed vertically in the fluidized separation chamber. The height difference between the bottom of the two copper tubes is 15 mm. The bottom of the copper tubes is coated with 1 mm thick filter cloth with a pore diameter of 15 μm to prevent the particles from entering the copper tubes. The top ends of the two copper tubes are respectively connected to the two interfaces of the same Alpha168P2500 differential pressure sensor (No. 11) by two plastic hoses, so that the pressure near the bottom of the two copper tubes can be detected. The measuring range of differential pressure sensor is 0–2500 Pa and accuracy is ±0.5% FS. PCB-208 force sensor (No. 9) is used to acquire particle impact force signals. Its maximum measuring value is 0.45 N, the measuring accuracy is ±0.5% FS, and the upper frequency limit is 36 KHz. Since the vertical vibration input from the bottom of the bed is transmitted from the bottom to top, the vibration mainly affects the motion of the particles in the vertical upward direction. So the force sensor is placed horizontally in the bed, and its circular sensing surface is parallel facing the gas distributor. The sensing surface made of piezoelectric material generates charges when it is exerted force. These charges are amplified by the charge amplifier and output in the form of voltage proportional to the external force. When the particles and rising gas hit the sensing surface, the component signal of the impact force along the vertical direction is collected. Both the differential pressure sensor and the force sensor are fixed on an iron shelf, which is not in contact with the VDMFB, that is, the two sensors are relatively stationary with the ground. The ICP acceleration sensor (No. 12) is fixed on the shaker to monitor the shaker displacement information in the real time. For the ICP acceleration sensor, its upper limit measurement is 250 g (g is gravity acceleration), and the measuring accuracy is ±0.25%FS. The particle impact force signal, the bed pressure signal in the fluidized chamber and the vibration displacement signal of the gas distributor are respectively recorded and transmitted to the computer (No. 14) in real time by the INV3060S data acquisition card (No. 13).

2.2. Materials

As dense medium, magnetite particles are fluidized under the collaborative effect of vibration and gasflow. The main physical properties of the magnetite powder are shown in Table 1. Its size is between 0.074 mm and 0.3 mm, belonging to the Geldart B particles, and the minimum fluidization gas velocity is almost equal to the minimum bubbling velocity [21]. After the magnetite particles which average density is 4.23 g/cm^3 are fluidized, the average density of the gas-solid two-phase bed is likely to reach 1.3 to 2.0 g/cm^3, which is consistent with the density of coal. So, magnetite powder is suitable as a medium for coal separation by density.

According to the Method for Float and Sink Analysis of Coal (GB/T 478-2008), zinc chloride and water were used to prepare solutions with a density of 1.3 g/cm^3, 1.4 g/cm^3, 1.5 g/cm^3, 1.6 g/cm^3, 1.7 g/cm^3,