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Process analysis of fine coal preparation using a vibrated gas-fluidized bed

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A B S T R A C T

Fine coal dry preparation becomes more and more significant for countries and regions which have insufficient processing water. Fine coal separation based on density segregation in a vibrated gas-fluidized bed (VGFB) does not use water and dense medium and has a good separation performance. This paper attempted to carry out a systematic process analysis of fine coal preparation in a VGFB. Particles distribution characteristics were experimentally studied and it was pointed out that a VGFB of fine coal having a periodic slugging behavior could obtain a good performance of density segregation. Furthermore, the effects of several operational factors on the stratification performance were studied using Box–Behnken response surface methodology (*RSM*) and the *RSM* analysis indicated that several factors including superficial air velocity, vibration intensity and bed height all had significant effects. Among these factors, the superficial air velocity behaved considerably more significant than others. Under the optimal operational conditions determined by the RSM analysis, the results of −6 + 3 mm fine coal preparation in a VGFB showed that the yield and ash content are 76.68% and 25.15% as to the clean coal product, and 23.32% and 60.08% as to the gangue product, respectively. The probable error *E* value is 0.18, indicating a good performance of fine coal dry preparation in a VGFB.

1. Introduction

Coal preparation that aims to physically remove mineral impurities from run-of-mine coal has long been adopted as an economic and effective way to produce clean coal [1]. The increasingly serious environmental problems caused by the pollutant emissions from coal utilization [2] make many countries contribute more effort to improve the ratio of run-of-mine coal to preparation. Especially for China, the world's largest coal producer and consumer [3], many measures including legislation, administrative regulations and financial support have been announced to achieve an objective of the proportion of run-of-coal to preparation no less than 70% by 2017. Coal preparation processes are generally classified into two categories: wet and dry processes. Recently, wet processes are dominant in industrial applications all over the world. Wet processes need large amounts of water [1], which is unfeasible for drought coal-producing areas. Almost 2/3 of China's coal resource deposit in Northwest China and most coal-producing areas in this region lack sufficient water to implement wet processes. Thus, China is urgent to develop dry processes. Meanwhile, several other countries including India, South Africa, Turkey and Australia also face similar problems of water shortage for coal preparation. Comparing with wet processes, dry processes are considerably environment-friendly with no water use and no slime water emission, and consequently, avoid fines dewatering and slurry confinement [4].

Recently, dry coal preparation has become one of the research hot spots in the field of coal preparation. Many scholars have made great efforts to develop high-efficiency dry coal preparation technologies and achieved a lot of innovative results. The development course and recent progress of coal preparation using air dense medium fluidized beds (ADMFB) have been well reviewed by Zhao et al. [5], Luo et al. [6], Sahu et al. [7] and Mohanta et al. [8]. Separation results reported recently by Zhao et al. [9], Mohanta et al. [10], Zhang et al. [11] and Sahu et al. [12] clearly evidence that this technology can provide an efficient approach to dry preparation of −50 + 6 mm coal. Other processes using no dense medium including dry jigging [13] and compound dry separation (FGX separator) [14] are reported in recent literature and their handling feed size range is approximately −80 + 6 mm and provide a simple, low-cost solution for dry preparation of steam coal before combustion.

However, with the increasing deployment of mechanized mining technology, the proportion of fine coal (−6 mm) in run-of-mine coal increases progressively. Fine coal dry preparation is imperative for efficient utilization of coal resource in drought regions. According to the processing principle, recent processes of fine coal dry preparation are mainly classified into two categories: dense medium separation [15–19], and improved pneumatic separation [20–24]. The former uses the dense medium, such as magnetite powder and fine sand, to

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form a bed of gas–solid suspension with certain density. Fine coal particles conduct sink–float processes depending on density difference. However, the feed coal having a smaller size needs dense media with a smaller size in order to obtain a good separation performance. A conventional gas-fluidized bed of finer dense media is prone to form some unfavorable fluidization phenomena such as channeling, agglomeration and intense bubbling [16,25]. Thus, scholars have carried out much research work on introducing external energy to a conventional ADMFB in order to enhance the gas–solid interaction and improve the fluidization quality. Some literature on the air dense medium magnetically stabilized fluidized bed [15,17], the air dense medium vibrated fluidized bed [16] and the Reflux classifier [18,26] reports that the probable error *E* values of these processes range from 0.066 to 0.07, indicating a good separation performance. However, the main unresolved problems of the dense medium separation are located in the stages of product purification and medium recovery. On the contrary, the improved pneumatic separation processes use no dense medium to separate fine coal based on hindered settling velocity difference. These processes reported in the literature include vibrated gas-fluidization separation [20,21] pneumatic jigging [23,27] and pneumatic table [22]. These processes avoid the problems imposed on the dense medium separation processes and have several advantages such as simpler handling procedure, lower operation costs, stable separation performance, leading to greater potential for industrial applications.

Heterogeneous particles in a fluidized bed tend to segregate depending on size/density difference [28]. For fine coal separation in a fluidized bed, good separation results need a good performance of density segregation. In the beginning, we had attempted to fluidize $-6+3$ mm fine coal by air flow solely. However, the results [29] showed that there were several disfluidized zones and short circuit channels within a fluidized bed after minimum fluidization. With the increase of the superficial air velocity, these disfluidized zones progressively disappeared and then slugging behavior happened. But this slugging behavior was unstable and a slug easily broke into several irregular bubbles during its rising through the bed. When further increasing superficial air velocity, a transition to turbulent fluidization happened and particles were well-mixed due to serious backmixing. Overall, we could not obtain good fluidization behavior and a satisfactory performance of density segregation for fine coal separation. Thus, we attempted to introduce vibration energy into a fluidized bed of $-6+3$ mm fine coal in this study and the results showed that the vibration could effectively destroy force chain and enhance gas–solid interaction. There were no disfluidized zone and short circuit channel after minimum fluidization. A significant improvement was the formation of periodic slugs under the synergistic function of fluidizing air and vibration. Particles with different density settled in the slugs with different velocity, leading to a good performance of density segregation [29]. Finally, the particle bed achieved a good stratification performance with clean coal particles on top and gangue particles on the bottom. However, in order to weaken the unfavorable effect of size segregation on the stratification performance, the size range of feed coal should be narrow and in general, the ratio of the maximum size to the minimum size of feed coal particles should be no more than 3:1. In this study, we focused on carrying out further studies on the particles distribution characteristics of fine coal in a VGFB under different conditions. The significance of the effects of the operational factors on the stratification performance of fine coal in a VGFB was also studied by using the Box–Behnken response surface methodology.

2. Experimental

2.1. Apparatus

The schematic diagram of the experimental apparatus is depicted in Fig. 1. A VGFB consists of three main parts: gas supply system, vibration generating system and fluidized bed. Fine coal particles are fluidized in a vertical cylinder with an inner diameter of 110 mm and a height of 400 mm which is made from transparent Plexiglass. Ambient air after filtering is dispersed by a sintered metal distributor and then enters the vessel and fluidizes granular particles. The vibration table deployed in this study is manufactured by China STI Co., LTD. and its operational parameters can be easily adjusted by a digital controller to generate oscillation motion with amplitude range of 0–10 mm and frequency of 1–400 Hz.

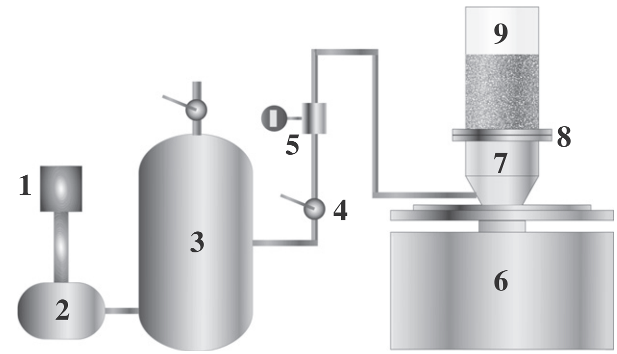

Fig. 1. Schematic diagram of the experimental apparatus. 1. Air filter; 2. roots blower; 3. tank; 4. valve; 5. gas vortex flowmeter; 6. vibration table; 7. air chamber; 8. air distributor; 9. vessel.

2.2. Materials

Fine coal having a size fraction of $-6+3$ mm is investigated in this paper and these particles belong to Geldart D particles [30]. The detailed properties are given in Table 1. The ash content of feed coal is 33.31%.

3. Results and discussion

3.1. Particles distribution characteristics

The characteristics of particles distribution of fine coal in a VGFB is essentially determined by the fluidization behavior. The regularity of bubbling behavior and the stability of gas–solid interaction are different under different fluidization behavior and then the characteristics of particles distribution are consequently different. The characteristics of particles distribution are studied by plotting ash distribution patterns (ADP) qualitatively and by measuring the ash segregation degree quantitatively. An ADP has a horizontal axis representing the ash content of a sample and a vertical axis representing a dimensionless height, $H^*=H/H_0$, where H is the height of investigated sampling layer of particles, H_0 is the initial height of particles bed. This pattern demonstrates the changes in ash content in the direction of bed height and a gentler slope of a pattern indicates a better performance of density performance. For fine coal separation in a VGFB, the particles distribution is expected to have a transition from a well-mixed state to a well-

Table 1
Detailed properties of fine coal investigated.

Density (g/cm^3)	Fraction (%)	Ash content (%)	$\delta \pm 0.1$	
			Density (g/cm^3)	Fraction (%)
−1.3	8.39	6.02	1.3	25.67
−1.4 + 1.3	17.28	10.31	1.4	39.55
−1.5 + 1.4	22.27	18.34	1.5	34.31
−1.6 + 1.5	12.04	25.83	1.6	18.66
−1.7 + 1.6	6.62	35.00	1.7	12.25
−1.8 + 1.7	5.63	44.52	1.8	16.55
−1.9 + 1.8	10.92	56.82	1.9	27.77
+1.9	16.85	75.97		
Total	100.00	33.31		