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Dry cleaning of fine lignite in a vibrated gas-fluidized bed: Segregation characteristics

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HIGHLIGHTS

- The segregation characteristics of lignite in a vibro-fluidized bed were studied.
- Both density-segregation and size-segregation depended on gas velocity.
- The bubble-drive flotsam–jetsam mechanism was responsible for the segregation.
- A fluidized bed assisted with vibration achieved higher separation performance.
- Both of frequency and amplitude had strong effects on the segregation behaviors.

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ABSTRACT

The segregation characteristics of fine lignite (−3 + 1 mm) in a vibrated gas-fluidized bed were examined. The pressure drop, ash contents and mass of a certain size fraction in lignite particles as a function of height through the bed, ash separation index, corresponding bed snapshots, and bubble size were investigated by varying superficial gas velocity. The effects of vibration parameters (frequency, amplitude, and vibration intensity) on segregation performance were also determined. Both density segregation and size segregation occurred as a function of superficial gas velocity. With increasing superficial gas velocity, the particle segregation changed to mixing state. An optimum air velocity existed to maximize segregation when fluidization velocities were between the minimum fluidization velocities of flotsam (clean coal) and jetsam (gangue). Bubble-driven flotsam–jetsam mechanism was responsible for the transition from segregation to mixing. The comparative ash segregation index and pressure drop characteristics between the vibro-fluidized bed and fluidized bed also confirmed this mechanism and suggested that application vibration achieved a high segregation performance at a low fluidization velocity because of reduced bubble sizes. The use of dimensionless vibration number (vibration intensity) alone to characterize segregation behavior could lead to misleading conclusions. Frequency and amplitude had strong effects on segregation performance.

1. Introduction

Coal is one of the primary energy sources in the world and accounts for the largest electricity generation (up to 41% of the total generation in 2010) [1]. To fulfill increasing energy demand and production of low-cost energy [2], low-rank coals are considered attractive resources because they are geographically dispersed, can be accessed easily, and have low mining cost [3]. Lignite (a type of low-rank coal), which accounts for approximately 13% of proven reserves, is directly burned for power generation in China [4]. However, direct use of these coals, which are composed of a substantial amount of ash-forming mineral matter [5] and moisture [6], not only reduces the efficiency of power plants but also generates additional particulate materials, SO_x, and emission of trace elements [7,8]. Thus, de-watering and de-ashing processes are introduced to utilize these lignite coals sustainably. Although not yet widely practiced by the power industry, coal cleaning technology can remove a large proportion of ashes and moisture prior to combustion. The produced clean coals can be fired directly into boiler/gasifier to enhance coal use efficiency, decrease carbon footprint, and eliminate environmental pollutions cost effectively [7].

Coal beneficiation is an essential component of clean coal technology, which covers all steps related to the energy produced

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from coals, i.e., coal mining, conversion processes, and flue gas treatment. Traditional coal beneficiation methods are mostly wet processes. These wet beneficiation methods are highly efficient in coal recovery; however, they suffer high process costs, high clay content of low-rank coals, and high operating costs for coal and waste slurry treatments [9]. Lack of water is also becoming a critical issue in mining areas worldwide. Therefore, the implementation of dry beneficiation is in great demand. Dry coal beneficiation technologies, including gas–solid-fluidized bed separator [10,11], gravity separator [12], air jigging [13], and FGX separator [14], provide an alternative solution. The gas–solid-fluidized bed is one of the attractive candidates for dry separation because it can efficiently beneficiate high-ash coarse (+6–50 mm) coals [15,16] and low-ash coals [17].

Dry separation using a gas–solid-fluidized bed generally has two main categories, namely, the “float-sink” or “segregation” of particle mixtures. Air dense medium fluidized bed (ADMFB) is a method based on the “float-sink” of particle mixtures. In utilizing the liquid-like properties of this bed, light (clean coals) and heavy coal particles (gangues) are stratified according to their densities in this medium. ADMFB provides efficient solutions for dry beneficiation of coarse coal (+6 mm). However, this technology interferes with excessive bubbling or turbulence of beds to some extent, thereby making it unsuitable for beneficiation of fine coals (−6 mm). Several improved ADMFB systems have been proposed to solve this problem. Luo et al. [18] applied mechanical vibration to strengthen the contact between gas and solid. Fan et al. [19] introduced a magnetically stabilized fluidized bed to separate fine coals. Macpherson et al. [10] developed a reflux classifier, which also offers an alternative to fine coal (−8 + 1 mm) beneficiation. Dong et al. [20] examined an active pulsing fluidized bed for fine coal separation. Dense medium recovery, product purification, and low processing capacity are the main concerns for these ADMFBs or improved ADMFBs.

Another dry separation method is based on the “segregation” of particle mixtures in a fluidized bed without any dense medium, which can eliminate obstacles that ADMFB encounters [21]. The segregation based on density difference is generally called “density segregation,” whereas that based on size difference is called “size segregation.” Yang et al. [22] examined the separation performance of fine high-rank coals in a vibro-fluidized bed. Their studies indicated that the separation performance largely depends on operational parameters and feed particle properties. However, segregation characteristics have not been fully studied. This information can aid the design of substantial particle properties for a given process and help to understand how coal cleaning equipment should be operated, designed, or modified to enhance separation performance.

In this study, segregation phenomena, the relative amount of density segregation and size segregation, and the bubble size at various air velocities were examined. The effects of vibration parameters (frequency, amplitude, and vibration intensity) on segregation characteristics were also determined.

2. Experimental

2.1. Experimental apparatus

Fig. 1 shows a schematic of the experimental setup. Compressed air was supplied by a Roots-type blower, which was connected to a flow control valve for measuring airflow rate. The resulting air flowed into a stainless steel plenum chamber and then entered into the distributor plate. To prevent bed materials from falling down, a filter cloth was placed on top of the distributor plate. The vertical cylindrical fluidized bed was made of transparent perspex, with an inner size of $\Phi 110$ mm × 400 mm. An electronic manometer was provided at different locations of the bed for measuring pressure drops. A bag filter was installed at the bed top to separate fines and gas. Vibration motions were supplied by an electromagnetic vibration system (DC-600-6, China STI Co., LTD) with an amplitude varying between 0 mm and 10 mm and a frequency varying between 1 Hz and 40 Hz. An Olympus i-SPEED 3 high-speed dynamic camera and the corresponding analysis system were used to record the bed snapshots.

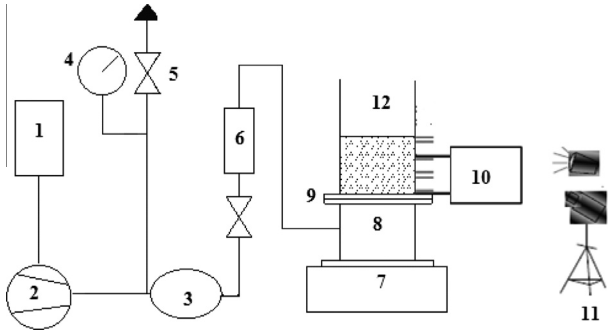

Fig. 1. Schematic diagram of the experimental apparatus. 1. Air filter; 2. roots blower; 3. tank; 4. pressure gauge; 5. valve; 6. rotameter; 7. vibration systems; 8. air chamber; 9. air distributor; 10. electronic manometer; 11. high-speed dynamic camera; and 12. filter.

2.2. Experimental procedure

During separation experiments, a typical lignite (Dayan coal in eastern Inner Mongolia) was used. The proximate and ultimate analyses are listed in Table 1. To avoid the impacts of surface moisture on the separation performance, the coal sample was air-dried. The particles were initially fluidized for 2 min according to our pervious study [22], and the fluidizing air was suddenly shut down. This static bed was divided into five layers in the axial direction. The ash content of each layer was analyzed. Each layer was also screened into different sizes of +2.5–3.0 mm, +2.0–2.5 mm, +1.5–2.0 mm, and +1.0–1.5 mm. Weight fractions x_D were measured. In our previous studies [22], the separation performance was evaluated by a statistical indicator (S), which is defined as follows:

$$S = \sqrt{\frac{\sum_{i=1}^{n}(A_i/A_0 - 1)^2}{n-1}}, \tag{1}$$

where A_i is the ash content of coal of ith sampling point; A_0 is the initial ash content of feed coal; n is the total sampling number. As can be inferred from Eq. (1), a large value of S suggested good segregation, which was favorable for fine coal separation.

3. Results and discussion

3.1. Characteristics of pressure drop

Pressure drop characteristics are considered among the most important variables in a fluidized bed. The minimum fluidization velocity can be determined from a pressure drop curve. Segregation patterns, which are the main concern of this study, can also

Table 1
The proximate analysis of Chinese lignite.

Sample	d (mm)	M_{ad} (%)	A_{ad} (%)	V_{ad} (%)	FC_{ad} (%)
Dayan	1–6	10.27	31.46	23.13	35.14