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Original Research Paper

# Effect of active pulsing air flow on gas-vibro fluidized bed for fine coal separation

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ABSTRACT

Coal is one of the primary energy sources in the world. Heavy consumption of coal causes severe environmental problems such as acid rain, fog, and dust. Because of increasingly severe water shortage, it is urgent to develop efficient dry separation methods. Air-dense medium fluidized beds (ADMFB) have been studied for dry beneficiation in the last decades. In this study, a pulsing air flow was introduced into ADMFB to form a gas-vibro fluidized bed (GVFB). The bed density of GVFB showed a stationary random signal with ergodic property. Using the vibration energy of an air flow, the fluidization quality and stability of bed density were enhanced. The bed density was suitable for fine coal separation in the middle-frequency region. The separation tests indicated that the effect of pulsing air flow is significant at a low gas speed, and the GVFB achieved effective separation and improved the quality of fine coal.

## 1. introduction

Because of excellent mass and heat transfer properties, gas–solid fluidized beds have been widely used in chemical engineering, drying, granulation, and combustion. In a concentrated-phase gas–solid fluidized bed, the presence of bubbles decreases the efficiency of mass and heat transfer between the gas and solid phases in the fluidized bed [1]. To decrease the size of bubbles in a gas–solid fluidized bed, enhance the gas–solid contact rates, and improve the mass and heat transfer, diverse special gas–solid fluidized beds have been developed, such as vibrating fluidized beds, magnetic fluidized beds, and fluidized beds with internals [2]. When an external force field is applied to a gas–solid fluidized bed, under certain conditions, the size of the bubbles in the bed decreases, and the distribution of the bubbles becomes more uniform. Furthermore, distributed secondary gas injection was used to reduce the bubbles in a bubbling fluidized bed. At high flow rates, smaller bubbles can be achieved [3–5]. A gas-vibro fluidized bed (GVFB) is also a special fluidized bed. GVFB changes the continuous air flow in a gas–solid fluidized bed into an active pulsing air flow with a periodic change of flow and introduces the forced vibration energy of air flow into the gas–solid fluidized bed, thus improving the quality of fluidization using the external force field [6–15]. A pulsation-assisted fluidized bed was investigated for drying, in which a fraction of the total flow oscillated intermittently and periodically [16,17]. GVFB is different from a vibrating fluidized bed: The vibration energy of a GVFB is provided by the vibration of air flow rather than the mechanical vibration acting on solid particles. Compared to a vibrating fluidized bed, in GVFB, no mechanical vibration is applied, and the failure rate of the separator is low. Therefore, the service life of GVFB is longer than a vibrating fluidized bed.

Coal is one of the primary energy sources in the world. The global primary energy consumption of coal in 2013 was 30.1%, the maximum value since the 1970s [18]. Heavy consumption of coal causes severe environmental problems such as acid rain, fog, and dust. The unnecessary gangues in coal can be separated by coal beneficiation. It forms the basis of efficient and clean processing of coal by separating minerals with higher contents of harmful elements such as pyrite. The conventional wet cleaning technology suffers from a large water consumption; therefore, efficient dry cleaning coal separation technologies are urgently needed.

Air-dense medium fluidized beds (ADMFB) have been used as a gas–solid fluidized bed technology in industrial productions [19–22]. ADFMB is also known as separating fluidized bed (SFB); it is used for the gravity separation of minerals [23–26]. In an

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**Nomenclature**

| | |
|---|---|
| $A(i)$ | ash content of the $i$th layer |
| $\bar{A}$ | weighted average of the ash content of all the layers |
| $E_p^{\dagger}$ | average of the whole $p_k^{\dagger}$ |
| $E_{Rp}(\tau)$ | average of the whole $R_p(t,\tau)$ |
| $E$ | expectations of runs in stationary test |
| $E_p$ | average of the whole $p(t)$ |
| $f_s$ | sampling rate |
| $m$ | number of whole captured pressure data in each subsample |
| $n$ | the layer number of multilayer sampling, number of whole subsamples |
| $N$ | fluidization number, which is the ratio of the max value of pulsating airflow velocity and the minimum fluidization velocity |
| $N_0$ | total value of $N_1$ and $N_2$ |
| $N_1$ | appearance times of + |
| $N_2$ | appearance times of − |
| $p(t)$ | time series of pressure fluctuation signals |
| $p_k^{\dagger}$ | average of the captured pressure data in $k$th subsample |
| $p_{\mathrm{k,m}}$ | $m$th captured pressure data in $k$th subsample |
| $r$ | run, i.e., the frequency of the symbols rotating through '+' and '−' |
| $R_p(t,\tau)$ | self-correlation function under the meaning of the average set |
| $R_k^{\dagger}(\tau)$ | average of the captured pressure data in $k$th subsample |
| $R_p^{\dagger}$ | average of the whole $R_k^{\dagger}(\tau)$ |
| $SD$ | standard deviation of runs in stationary test |
| $T$ | sampling time of each subsample |
| $u_f$ | minimum fluidization velocity |
| $v_p$ | amplitude of pulsating gas velocity |
| $Z$ | statistics value |
| *Greek letters* | |
| $\mu_k$ | average value of $k$th subsample |
| $\varphi_k$ | mean square value of $k$th subsample |
| $\sigma_k$ | standard deviation of $k$th subsample |
| $\psi$ | mid-value of whole subsamples |
| $\tau$ | time delay |
| $\gamma(i)$ | yield of the $i$th layer |

SFB, fine coal and Geldart B-type magnetite powders are used as composite medium solids, whereas compressed air is used as the fluidized gas, thus forming gas–solid suspended solids with a certain density. Then, mineral particles are fed into an SFB following the Archimedean principle: The particles lighter than the suspended solid float upward, whereas the particles heavier than the suspended solid sink, thus separating minerals with different densities [27–32]. However, because the size of bubbles in ADMFB is large and the effective particle size of separation is +6 mm, the effect of ADMFB on fine coal separation with a size of −6 mm is poor. GVFB was proposed for fine coal beneficiation in the recent years. The size of the bubbles was reduced, and fine coals with −6 + 3 mm size fraction were separated efficiently. Clearly, the ash and sulfur contents of the coal were reduced. In this study, stationary and ergodic tests of the density signals in GVFB were conducted. Separation tests for fine coal with −3 + 1 mm size fraction were conducted to evaluate the separation efficiency of the GVFB.

## 2. Experimental

The diagram of the experimental system used in this study is shown in Fig. 1. An active pulsating air flow was generated using a butterfly driven by an electric motor. The pulsation frequency was controlled using an inverter. The scheme of gas velocity *vs.* time is shown in Fig. 2. The minimum value of the gas pulsating velocity is zero, and the maximum value (the amplitude) of the gas pulsation velocity is $v_p$. The diameter of the fluidized bed was 200 mm, and the height of the static bed was 100 mm. A porous plate was used as the air distributor. The structure of the porous plate is shown in Fig. 1. The photo was recorded using a scanning electron microscope (HV: 25 kV, MODE: SE, MAG: 40×). The pressure drop of the air distributor was higher than that in the bed. Geldart B-type magnetite powders with a size of 74–300 μm and an average particle diameter of 232 μm were used as the separating medium. Micro pressure difference sensors (Alpha Instruments, output: 0–5 V, accuracy: 1% FS, capacity: 0–2500 Pa) were used to collect the pressure drop in the bed. By measuring the pressure difference between two points in the bed, the average density was calculated using $\Delta p = \rho g \Delta h$, where $\Delta p$ is the pressure difference and $\Delta h$ is the height difference in the fluid. To study the temporal–spatial distribution of GVFB bed density, the SFB was divided into three layers in the vertical direction: upper, central, and lower layers. The measuring points of the layers were as follows: upper layer, 90 mm to the air distributor; central layer, 60 mm to the air distributor; lower layer, 30 mm to the air distributor. In each layer, a total of 25 measurement points were set. The measurement point of 1# was set at the central point of the cross-section of fluidized bed, whereas the measurement points of 2–25# were arranged at the polar coordinates. Considering that the diameter of the model machine of SFB was 200 mm, the polar radii of the measurement points were 30 mm, 60 mm, and 90 mm, respectively. The spacing of the polar angle was π/4 rad, and the measurement points were uniformly distributed in the range 2π rad. Fig. 3 shows the layout of the measurement points. To measure the bed density more accurately and evaluate the fluctuation characteristics of the bed density over time, the sampling frequency of the data acquisition device was set as 128 Hz, and the sampling time for each sampling was set as 80 s according to the Shannon–Nyquist sampling theorem and the response speed of sensor.

In this study, the operating conditions of the fluidized bed are listed in Table 1. The minimum fluidization velocity of the GVFB at different gas pulsation frequencies was tested according to the relationship between bed pressure drop and superficial gas velocity [33], and the results are listed in Table 2. Based on the minimum fluidization velocity, the amplitude and mean value of the gas pulsation velocity at different fluidization numbers and gas pulsation frequencies can be calculated, as listed in Table 3.

## 3. Theory & method

### 3.1. Stationary and ergodic tests

The bed density and pressure fluctuation of GVFB are mainly caused by the movement of bubbles. The movement of bubbles is uncertain and can be regarded as a random system; therefore, the bed pressure fluctuation can be analyzed using the processing method of random signals. During the study of the fluctuation