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Analysis of interaction between bubbles and particles in a dense gas-vibro fluidized bed

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HIGHLIGHTS

- Bubbles in a dense gas-vibro fluidized bed is equivalent to special springs.
- A dynamic model was developed for the interaction of bubbles and particles.
- Interaction between bubbles and particles is analyzed using modal analysis.

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ABSTRACT

Gas-solid fluidized beds are widely used for their excellent characteristics of heat and mass transfer. An active pulsating air flow is introduced into a dense gas-solid fluidized bed, forming a dense gas-vibro fluidized bed (DGVFB), to modify the fluidization quality. Interaction between the bubbles and particles in the DGVFB was investigated based on the results of numerical simulations and experiments. Micro-bubbles in the DGVFB were regarded as springs, and therefore, the interaction between the bubbles and particles was considered to be equivalent to a linear vibration system with n degrees of freedom. A dynamic model for the vibration system was developed, and modal analysis was conducted. Results of this theoretical analysis showed that the dominant frequency of pressure fluctuations in the DGVFB was equal to the frequency of active pulsating air flow. The dynamic model described the interaction between the bubbles and particles effectively in the DGVFB at low gas pulsating frequency, and shallow fluidized beds.

1. Introduction

Gas-solid fluidized beds are popular in the chemical, oil, powder, pharmaceutical, and food industries due to their excellent characteristics of heat and mass transfer. Fluidization can be divided into two types, aggregative fluidization, and particulate fluidization (Kwauk et al., 2000; Li et al., 2003a). In a dense gas-solid fluidized bed, as there are many bubbles, the fluidization is named as a bubbling fluidized bed. This fluidized bed is considered to be of the aggregative fluidization type. Bubbles in the fluidized bed can reduce the contacting rate between the gas phase and the solid phase, and therefore, the efficiency of heat and mass transfer can be reduced (Hongzhong and Mooson, 2013). The fluidization quality can be modified by introducing external excitation into the gas-solid fluidized bed, such as vibrational energy, magnetic fields, and acoustic fields. A gas-vibro fluidized bed (GVFB) in which the velocity of the fluidizing agent varies periodically, is a specialised fluidization that introduces the vibrational energy of an active pulsating air flow into the fluidized bed (Gawrzynski and Glaser, 1996; Ireland et al., 2016; Walzel, 2013).

The behavior of the bubbles is frequently used to evaluate the influence of active pulsating air flow over a continuous flow bed. The effect of gas pulsation frequency on the size and distribution of bubbles have been studied widely. These studies showed that bubbles which were acted upon by the active pulsating air flow, could have their bubble size reduced compared to the continuous flow bed (Fujikawa et al., 2003; Khosravi Bizhaem and Basirat Tabrizi, 2013; KSksal and Vural, 1998; Li et al., 2009; Wang and

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Rhodes, 2005). By introducing an active pulsating air flow, the minimum fluidization velocity can be reduced (Khosravi Bizhaem and Basirat Tabrizi, 2013; Sobrino et al., 2008). Particles become more readily fluidized by the pulsating air flow. The distribution of temperature was found to be more uniform in the GVFB by Jezowska (Jezowska, 1993). The heat and mass transfer efficiency can be improved by 17–33% in a fluidized bed of Group B particles (Zhang and Koksal, 2006). Acted by the active pulsating air flow, the fluidization quality can be improved efficiently (Ali et al., 2016; Gui and Fan, 2009; Pandit et al., 2007; Saidi et al., 2014, 2015; Wang and Rhodes, 2003). Therefore, the GVFB is used for drying (Ambrosio-Ugri and Taranto, 2007; de Souza et al., 2010; Gawrzynski and Glaser, 1996; Li et al., 2004; Nitz and Taranto, 2007; Rosa et al., 2013; Zhang and Koksal, 2006) and coating (Li et al., 2003b; Li and Liu, 2008; Tiznado et al., 2014).

Due to the high fluidization quality of the GVFB, it was employed for the de-ash and desulfurization of fine coal (Dong et al., 2015a). In previous studies, the characteristics of bubble behaviors and pressure fluctuations were investigated (Dong et al., 2014, 2015b; Duan et al., 2015), and the de-ash and desulfurization efficiency for fine coal with −6 + 1 mm size was studied. In order to investigate the interaction between bubbles and particles in a dense gas-vibro fluidized bed (DGVFB), a novel dynamic model was developed in this study. Micro-bubbles in DGVFB were regarded as springs, and the interaction between bubbles and particles were considered to be equivalent to a linear vibration system. Modal analysis for the vibration system was conducted. Finally, experiments were utilised to determine the accuracy of the model.

2. Experimental and numerical simulations

The experimental system is shown in Fig. 1. An active pulsating air flow was compressed into the fluidized bed using a butterfly valve driven by an electric motor. Two porous plates in which the mean pore size was 5 μm were used as the air distributors (Dong et al., 2016a). The fluidized bed was a glass cylinder with a diameter of 200 mm. In the fluidized bed, magnetic powders were used as heavy mediums, whose true density was 4.6 g/cm^3, with a bulk density of 2.35 g/cm^3, and with a mean particle size of 232 μm. The static bed height was 100 mm. Four pressure transducers were used to measure the pressure fluctuations in the bed, and were installed in the vertical direction. Probe indexed 1# was set at the bed bottom, probe indexed 4# was set at the 90 mm bed height, and the intervals between probes were 30 mm. A high-speed camera recorded images of the fluidized bed, with a capture rate of 2000 frames/s. This allowed the bubbles in the fluidized bed to be clearly observed.

Computational fluid dynamics was used to simulate the fluidization process of the air dense medium fluidized bed (ADMFB, which is used for dry coal beneficiation (Lv et al., 2015; Sahu et al., 2015; Wang et al., 2016; Zhang et al., 2014; Zhao et al., 2011, 2017)) and DGVFB. The numerical simulations were conducted for a two-dimension fluidized bed. The width of the fluidized bed was 200 mm. The static bed height was 100 mm. The Syamlal-O'Brien drag model was employed to predict better results (Wang et al., 2013). The results of the numerical simulations are shown in Fig. 2. In the ADMFB, there were many bubbles in the bed. In the DGVFB, there are two dilute-phase zones in the bed, and no obvious large bubbles. This is confirmed by the experimental results, as shown in Fig. 3. It means that when acted by the active pulsating air flow, the fluidization quality of a dense fluidized bed can be modified. It was observed that the dilute-phase zone contained many micro-bubbles.

Based on the characteristics of the bubbles in the DGVFB, analysis of the interactions between the bubbles and heavy mediums was conducted below. Due to the compressibility and surface tension of the bubbles in the fluidized bed, the bubbles are considered to be elastic in nature. During the movement from the bed bottom to the free surface, interactions between the heavy medium around the bubbles, and bubbles themselves occurs, and this affects the diameter of bubbles. Therefore, a bubble can be regarded as a kind of special spring. This interaction between these bubbles and the heavy medium particles can be then considered to be equivalent to the interaction between springs and particles.

3. Theoretical analysis

3.1. Interaction between single bubble and particles

The interaction between a single bubble and the heavy medium surrounding it is analyzed. Bubbles in the fluidized bed are assumed to be spherical. During the interaction between a bubble and the heavy medium, the volume of the bubble varies near an equilibrium position. The initial volume is V_0, and the initial radius is r_0. The volume ranges from $V_0 - V$ to $V_0 + V$ as shown in Fig. 4.

During a time interval of dt, the diameter of a bubble ranges from r to $r + dr$, and the variable quantity of volume is dV. The gas-solid suspension around the bubble which can be affected by the variation of the bubble, can be also be assumed as a suppositional sphere, and this diameter ranges from R to $R + dR$ (Fig. 5). Therefore, the following equations can be achieved:

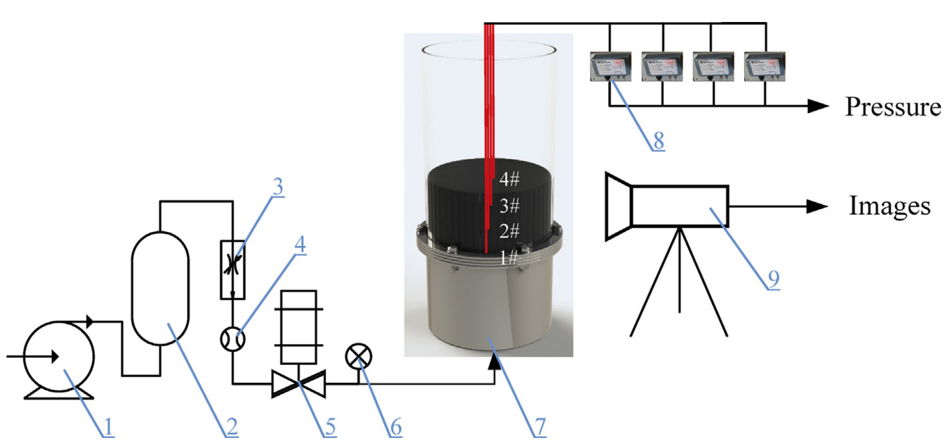

Fig. 1. Schematic diagram of experimental setup. 1-Air blower; 2-air tank; 3-flowmeter; 4-valve; 5-electric butterfly valve; 6-pressure gage; 7-fluidized bed; 8-pressure transducers; 9-high-speed camera.