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Original Research Paper

Characterization of temporal and spatial distribution of bed density in vibrated gas-solid fluidized bed

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A B S T R A C T

This study uses a Φ 200 mm × 900 mm vibrated gas-solid fluidized bed (VGFB) with −0.3 + 0.074 mm magnetite powder was utilized to characterize the temporal and spatial distribution of bed density in VGFB and the influence of bubble movement on fluctuations in bed density. The results indicate that the bed density decreases with an increase in gas velocity (U) and the frequency (f) and amplitude (A) of vibration and that the bed density spatial distribution is lower in the central region but higher in the border regions. The standard deviation of the density first increases then decreases and finally tends to stabilize with an increase in apparent gas velocity. Moreover, when A = 2 mm, f = 25 Hz and U = 14 cm/s, the density distribution is 1.82–1.88 g/cm^3 and the fluidization state is improved. The energy of the pressure signal increases with an increase in gas velocity and vibration amplitude. In particular, the low-frequency band of the pressure signal exhibits the highest amplitude and energy, which reveals that bubbles are the main cause of pressure fluctuation. Furthermore, the bed density decreases with an increase in bubble generation frequency, and the relationship between these follows the ExpDec 2 mathematical equation.

1. Introduction

Due to its being a highly efficient reactor, the vibrated gas-solid fluidized bed (VGFB) has been used extensively in numerous industrial processes, including catalytic processes, drying and coal separation [1–4]. In the field of air-dense medium dry coal preparation, the coal separation process is completed in a gas-solid suspension of a certain density. Therefore, the effectiveness of coal separation depends on the uniformity and stability of the bed density [5–7]. The gas-solid suspension is an emulsified phase composed of solid particles and gas, whose fluidization characteristics are related to the gas velocity, vibration parameters and particle properties. When more gas is present in the bed than is required for its critical fluidization, excess gas passes through the bed in the form of bubbles and perturbs the uniformity of the bed density negatively impacting the coal separation environment. In order to inhibit the formation and merging of bubbles and prevent physical phenomena such as short circuiting of air flow and the agglomeration of particles, VGFB has been used as a clean dry coal preparation technology, as it promotes bed fluidization and forms a density segregation environment suitable for fine coal separation [8–11]. Although VGFB exhibits pseudo-fluid characteristics, it is not a single phase fluid with uniform and stable density; inhomogeneity in the density has been found to arise on a macroscopic scale as well as in the local axial and radial bed microstructure [12–14]. Moreover, the temporal and spatial distribution of the bed density in VGFB and the effects of different operating conditions on bed fluidization have not been fully characterized.

Extensive and systematic research has been conducted into VGFB, primarily focusing on the characteristics of the motion of bubbles and particles in the bed [15], the mechanism by which vibration energy is transmitted [16] and their effectiveness for the dehydration [17] and separation [18] of fine coal. Cano-Pleite et al. [19,20] studied the characteristics of the motion of bubbles and particles in a 2D vibrated fluidized bed through a combination of digital image analysis (DIV) and particle image velocimetry (PIV). The results demonstrated that both the center of mass and

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Nomenclature

f	vibration frequency, Hz	Δh	height difference between two points, mm
A	vibration amplitude, mm	ρ_{ij}	bed density of measuring point, g/cm^3
U	gas velocity, cm/s	ρ	mean bed density, g/cm^3
Λ	vibration strength	δ	standard deviation of bed density
I	bed layers	$x(t)$	pressure signal
J	measuring points	$P(\omega)$	power spectrum of pressure signals
ΔP	differential pressure of two points, Pa		

the surface of the bed oscillate with a frequency equal to that of the vessel. The bed surface oscillates in phase opposition with the bed vessel, reflecting cyclic compression and expansion of the bulk of the bed. Wang et al. [21,22] used a pressure sensor for simultaneous pressure detection at different axial heights in the bed so as to analyze the within-bed pressure wave transmission process and vibration energy dissipation mechanism. The results demonstrated that energy is generated by the vibration of the table and transmitted to the granular bed by an air gap formed between the air distributor and the granular bed. They also showed that the pressure waves reflect and superimpose between the surface and the fluidized bottom of the bed, causing most of the energy dissipation to occur in the bed interior. Peter Müller et al. [23] analyzed the influences of moisture content and cyclic moisture loading and unloading on the mechanical properties which explained the evolution mechanism of the elastic–plastic force–displacement behavior better. Meanwhile, the study of particle characteristics provides a theoretical basis for the wave attenuation in a gas-solid suspension in the vibrated fluidized bed. In Fan et al. [24], the drying of alcohol sludge was studied in a vibrated fluidized bed with inner-heating tubes. The results showed that the final moisture content of the sludge could be decreased through reasonable increases in the gas velocity, gas temperature, vibration frequency and the power of the inner-heating tubes. The dry preparation of −6 + 3 mm and −3 + 1 mm fine coal using VGFB was extensively studied by Yang et al. [25–27]. The results clearly evidence that fine coal preparation in a VGFB with periodic slugging behavior can achieve effective density segregation, and indicate that the amplitude and frequency of the vibration and the superficial air velocity all have significant effects on the slugging behavior. These studies also quantitatively examined the dynamics of the coalescence of bubbles into an adjacent slug.

Despite this extensive study, little research has been conducted into the density distribution in VGFB. Owing to the high concentration of particles in a VGFB, quantitative analysis methods cannot be used to study its fluidization characteristics. Furthermore, what studies there have been into the characteristics of the bed density distribution have mainly concentrated on an ordinary gas-solid fluidized bed and a 2D VGFB [28–31]. Therefore, it is of great importance to conduct systematic research into temporal and spatial variations in bed density in a VGFB, in order to determine the fluidization characteristics inside the VGFB and the dynamic behavior of bubbles.

In this study, we aimed to characterize the dynamic fluidization behavior of fluidized beds by conducting comprehensive experiments to assess the spatial and temporal variation in bed density under different operating conditions. Based on the linear relationship between bed density and pressure drop, differential pressure sensors were used to measure the pressure signal at different bed positions and so obtain the bed density at the corresponding position [32]. We additionally studied the variation in the standard deviation of bed density fluctuation, with the objective of revealing the regularity of the intensity of bed density fluctuation in the VGFB under different operating conditions. The Welch power spectrum method was used to study the influence of bubble movement on bed density fluctuation, and a regression fitting equation was established to fit the relationship between bed density and the frequency of bubble generation.

2. Experimental procedure

2.1. Experimental apparatus

The device diagram in Fig. 1 illustrates the experimental apparatus used in this study. It is composed of a fluidized bed vessel, air supply device, pressure signal measuring device, and adjustable vibrator. Magnetite powder with a 0.187 mm average diameter (−0.3 + 0.074 mm) and an average density of 4.63 g/cm^3 was selected as the bed medium for the experiments (see Section 2.2). The experiments were executed in an organic glass column bed with a height of 900 mm and an inner diameter of 200 mm, which was placed on the vibrated table. The air was controlled by a tube valve, and the airflow rate was read directly from a Vortex flowmeter. The vibration frequency, f, and amplitude, A, were adjusted using cooperative feedback from the computer and sensors on the vibration table. In each experimental run, the magnetite powder was fluidized in the bed under the combined action of the airflow and vibration energy, and the fluidization was retained for 2 min. Three pressure differential transmitters (168P2500DB1NB, Alpha Instruments, USA) and one data logger (cDAQ-9178, National Instruments, USA) were utilized to record the pressure fluctuation signals in the bed and output to MATLAB in a dedicated data format by mean of COINV DASP software (v10, Coinv, China). Owing to the linear relationship between the bed density and pressure drop signals, the bed density at different bed positions under different gas velocity and vibration conditions was obtained by collecting the pressure fluctuation signal at that positions. Moreover, the bed complex fluidization characteristics is also closely relating to the particle characteristics and structural modifications, therefore, the discrete particle properties and the influence of possible structural modification and thereby on the mechanical properties should be considered in future experiments. Because pressure drop signals have a fast response, high-quality test signals were obtained through the use of high-precision dynamic pressure sensors with a measurement accuracy of 0.5%. In order to ensure that the sampling signals would be able to represent the VGFB fluidization states precisely and accurately, the sampling frequency was 1024 Hz and the sampling duration was 30 s in the experiments.

2.2. Material properties and experimental conditions

Particles of magnetite powder were selected as the medium solid with which to study the temporal and spatial distribution of the bed density in VGFB, mainly based on industrial coal

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