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Evaluation of air-dense medium fluidized beds with pulsatile inlet air

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ABSTRACT

A two-dimensional Eulerian-Eulerian two-fluid model is established to study the effects of pulsatile inlet air on an air-dense medium fluidized bed (ADMFB). The bed-volume expansion and dissipation rate are introduced to evaluate the overall fluidization and energy loss of the bed, respectively. The standard deviation and fast Fourier transform signal processing technique are also employed in the investigation of bed quality. The results show that significant flow phenomena occur around bubbles with both the greatest energy loss and large gradients of pressure and velocity. For inlet air without pulsation, the Reynolds number is the major dimensionless parameter influencing the bed flow. Both the bed-volume expansion and dissipation rate (dimensionless) linearly increase with the Reynolds number. As the inlet air flows faster and more kinetic energy is transferred into the bed, the uniformity of the bed decreases and relatively less energy is lost. For inlet air with pulsation, the Strouhal number is the major influential dimensionless parameter. The bed-volume expansion drops to nearly a constant as the Strouhal number increases. The non-linear effects of the Strouhal number on the dissipation rate of the bed are approximated through a logarithmic function. With an increase in pulsation frequency, the bed fluctuation decreases and more energy is lost. The pulsation amplitude should be small to form an ADMFB with uniformity and relatively low energy loss. In general, pulsation inhibits bed-volume expansion and greater energy loss is incurred. In practice, pulsation might be used to maintain a bubbling state in a bed with high kinetic energy.

1. Introduction

Air-dense medium fluidized beds (ADMFBs) have been increasingly used to beneficiate low-rank coal of lignite and coal in water-deficient areas or to increase the environmental friendliness of the process (Chen and Wei, 2003; He et al., 2013a). Achieving a high efficiency of coal beneficiation requires ADMFBs to have a favorable density distribution and stable pressure drop (Askarishahi, 2014; Bi, 2007; He et al. 2013a; He et al., 2013b; He et al., 2013c). Currently, available field assistance approaches that can enhance bed fluidization include magnetism, electricity, (ultra)sound, and vibration (Hristov, 2007). Pulsating inlet air is also an attempt to improve ADMFBs in coal beneficiation through a reduction in bubble size and an increase in the uniformity of the bed density distribution (Donget al., 2013). In general, however, regulation and control of beneficiation density in ADMFBs has not been described well (He 2013b).

The quality evaluation of ADMFBs has not yet been widely accepted (Puncochar 2003). Quantitative estimation of the influence of pulsation on ADMFBs is even more limited. Ngo et al. introduced an index, ***UI***, to indicate the uniformity of the particle distribution, using the built-in volume-average function of a commercial software package for computational fluid dynamics (CFD), ANSYS FLUENT™ (ANSYS Inc., Canonsburg, PA, USA) (Ngo 2015),

$$UI = 1 - \frac{\sum_{i=1}^{n} |\psi_i - \overline{\psi}_a| A_i}{2|\overline{\psi}_a| \sum_{i=1}^{n} A_i} \quad (1)$$

where ψ_i is an arbitrary variable, $\overline{\psi}_a$ is the average of ψ_i, and A_i is the cell volume in three dimensions or cell area in two dimensions (Ngo et al., 2015). Puncochar et al. introduced the two thermodynamic concepts of entropy and dissipation rate to describe the disorder of an ADMFB (Puncochar and Drahos, 2003; 2005). Their study showed that the standard deviation of a quantity can also work as a quantitative indicator of the bed quality. Puncochar et al. explained and experimentally verified the linear dependence of the standard deviation of the total pressure on the excess gas velocity (Puncochar and Drahos, 2005).

Dimensionless analysis, as a powerful tool in research, has been applied in the study of fluidized beds. The major dimensionless parameters of ADMFBs include the Reynolds number (the ratio of inertial forces to viscous forces in air), the Archimedes number (the ratio of buoyant force to viscous forces), Galilei number (the ratio of

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gravity forces to viscous forces), Froude number (the ratio of inertial forces to gravity forces), and density ratio of particles to fluid (Kuwagi et al., 2014). For field-assisted fluidization, more dimensionless parameters are introduced due to field effects. For example, characterization of magnetism-assisted fluidization requires the granular magnetic Bond number (the ratio of gravity and magnetism forces), Filippov number, Rosensweig number, Kwauk number, and Siegell number (Hristov, 2007). In an ADMFB with pulsatile inlet air, two additional dimensionless parameters are involved, the Strouhal number (the ratio of inertial forces due to unsteadiness to those due to advection in the flow) and the ratio of two velocity components of the inlet air, the pulsatile and stable (detailed definitions depend on the pulsatile pattern of the inlet air). Particles are often divided into four groups, Geldart A, B, C, and D, according to the particle size, i.e., 20–100, 40–500, 20–30, and over 600 μm, respectively (Geldart, 1973). Scaling of fluidized beds works for Geldart B and C particles, but not for Geldart A particles (Lim et al., 1995). High-pressure fluidized beds do not follow such scaling rules, either (Lim et al., 1995).

This paper is based on our previous work done by Dong et al. in 2013, the pioneering study of pulsatile inlet air in ADMFB applications (Dong 2013). Focusing on the bubble rise velocity at limited pulsation frequencies, we have not sufficiently investigated the pulsation effects of the inlet air on bed fluidization. Here the Strouhal number, together with the Reynolds number, is particularly introduced to present the characteristics of pulsation. Due to the pulsation features of the inlet air, a fast Fourier transform (FFT) is specifically used to process data and analyze results. We also make efforts to quantitatively describe fluidization through the definition of new quantities, for example, the thermodynamics-related quantity of dissipation and statistical methods.

This is a numerical study of ADMDBs. There are several widely accepted methods, for example, the two-fluid method (TFM), lattice Boltzmann method (LBM), discrete-particle method (DPM), discrete-bubble method (DBM), discrete-element method (DEM), and particle-in-cell (PIC) method. TFM and LBM are regarded as Eulerian-Eulerian models and DEM, DPM, and PIC as Eulerian-Lagrangian models (Andrews 1996; Deen et al., 2007; Garg et al., 2012; van der Hoef et al., 2004). These models have been accessible through either commercial software packages, open sources, or both. The commercial software packages include ANSYS FLUENT™, Barracuda™ (CPFD Software, LLC, Albuquerque, NM, USA), and EDEM™ (DEM Solutions Ltd., Edinburgh, UK), to name a few. OpenFoam (ESI Group, Paris, FR) and MFIX (multiphase flow with interphase exchanges, NETL, USA) are two of the popular open source packages on fluidization (Garg 2012). Currently we concern ADMFBs at the scale of bubbles, which is a comfortable zone for TFM, a mature Eulerian-Eulerian method, to handle. Further, considering computation robustness and software accessibility of ANSYS FLUENT™, we use TFM to solve the ADMFB problem.

2. Method

2.1. Models

Fig. 1 shows a sketch of a two-dimensional ADMFB. The bed is made of magnetite particles of Geldart B type. The height of the bed at rest is h_0. Fifty air inlets with an opening of 3 mm each are evenly located in a sieve at the bottom (Fig. 1). The bed is fluidized as it gains sufficient energy from the inlet air.

We generally follow the methods described in our previous studies (Dong 2013; He 2013a; He 2013b; He 2013c). In the TFM, the continuity and momentum equations are (i= a, b. a: air, b: bed):

$$\frac{\partial}{\partial t}(f_i\rho_i) + \nabla\cdot(f_i\rho_i\vec{V_i}) = 0 \quad (2)$$

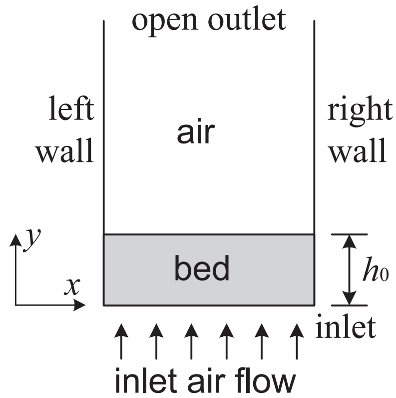

Fig. 1. Sketch of a fluidized bed.

$$\frac{\partial}{\partial t}(f_i\rho_i\vec{V_i}) + \nabla\cdot(f_i\rho_i\vec{V_i}\,\vec{V_i}) = -f_i\nabla p + \nabla\cdot\overrightarrow{\overrightarrow{\tau_i}} + f_i\rho_i\vec{g} + \vec{S_i} \quad (3)$$

where ρ_i is the density, $\vec{V_i}$ is the velocity vector, p is the pressure, $\vec{g}$ is the gravity vector, f_i is the volume fraction, $\overrightarrow{\overrightarrow{\tau_i}}$ is the stress tensor, and $\vec{S_i}$ is the source term. The stress tensor is written as $\overrightarrow{\overrightarrow{\tau_i}} = f_i\mu_i(\nabla\vec{V_i} + \nabla\vec{V_i}^T)$, where μ_i is the viscosity. The source term $\vec{S_i}$ is the summation of interaction forces between phases, lift forces, wall lubrication forces, virtual mass forces, and turbulent dispersion forces. The forces can be seen in detail in the ANSYS FLUENT documentation on the Eulerian model theory of multiphase flows (ANSYS, 2012). For the TFM in this study, the Gidaspow models are used for granular viscosity and the fluid-solid drag function, while the models of Lun are used for the granular bulk viscosity, solid pressure and radial distribution, and the granular temperature is algebraic (ANSYS, 2012).

The volume fraction function follows the convective equation,

$$\frac{\partial f_i}{\partial t} + \nabla\cdot(f_i\vec{V_i}) = 0 \quad (4)$$

where the summation of f_a and f_b may be set at a value less than unity.

The standard k-ε equations are used to solve turbulence,

$$\frac{\partial}{\partial t}(f_i\rho_i k_i) + \nabla\cdot(f_i\rho_i k_i\vec{V_i}) = \nabla\cdot\left[(\mu_i + \frac{\mu_{ti}}{\sigma_{ki}})\nabla(f_i k_i)\right] + G_{ki} + G_{bi} - f_i\rho_i\varepsilon_i \quad (5)$$

$$\frac{\partial}{\partial t}(f_i\rho_i\varepsilon_i) + \nabla\cdot(f_i\rho_i\varepsilon_i\vec{V_i}) = \nabla\cdot\left[(\mu_i + \frac{\mu_{ti}}{\sigma_{\varepsilon i}})\nabla(f_i\varepsilon_i)\right] + C_{1\varepsilon i}(G_{ki} + C_{3\varepsilon i}G_{bi}) - C_{2\varepsilon i}\rho_i\frac{\varepsilon_i^2}{k_i} \quad (6)$$

In the above equations, μ_{ti} is the turbulence viscosity; G_{ki} and G_{bi} are the generation of turbulent kinetic energy due to mean velocity gradients and buoyancy, respectively; $C_{1\varepsilon i}$, $C_{2\varepsilon i}$, and $C_{3\varepsilon i}$ are constants; and σ_{ki} and $\sigma_{\varepsilon i}$ are the turbulent Prandtl numbers (the ratio of viscous diffusivity and thermal diffusivity) of k and ε, respectively. More details can be found in the ANSYS FLUENT documentation (ANSYS, 2012).

For the boundary conditions, the inlet air velocity, u_{in}, at the bottom (Fig. 1) is given,

$$u_{in} = u_t\cos(2\pi f_{Hz}t) + u_0, \quad (7)$$

where f_{Hz} is the frequency of the inlet air pulse, u_t indicates the pulsation amplitude, and u_0 is the stable velocity component. The top of the domain, open to air, is set as free outflow. No-slip conditions are applied at the walls.

2.2. Parameters and scaling

Table 1 lists the major parameters of the ADMFB.