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Influences of the fluidizing and spouting pulsation on particle motion in spout-fluid beds

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ABSTRACT

Effects of variable airflow on particle motion in spout-fluid beds are studied. Computational fluid dynamics using Navier–Stokes equations for the gas phase coupled with the discrete element method using Newton's laws for the solid phase have been employed. Results indicate that increasing the fluidizing velocity diminishes dead zones and increases both the total height of the bed and the traversed distance by particles in the steady spout-fluid bed. In pulsed airflows, two configurations are investigated, namely, the spouted pulsed-fluidized bed with pulsed flow of the fluidizing velocity, and the pulsed-spouted fluidized bed with pulsed flow of the spouting velocity. The positive effect of pulsation on particle motion is shown and the effects of parameters, such as amplitude and frequency, on the dynamics of the bed are investigated in each configuration. An increase of up to 19% in traversed distance is found for the range studied, which suggests flow pulsation as a promising technique for increasing particle mixing in spout-fluid beds.

Introduction

Fluidized and spouted beds are widely used in industrial applications such as drying, coating, mixing, combustion, gasification, and granulation. In these reactors, the exposure of particles to air flow leads to fluidization and circulation. In fluidized beds, the gas enters uniformly from the whole base, whereas in the spouted beds it enters locally from a central nozzle or slot. The special feature of particles in a fluidized bed is the random motion arising from the generation and collapse of bubbles; however, there is a regular circulation of particles with the upward motion in the dilute spout and the downward motion of the dense annular flow in the spouted bed. The major drawback in fluidized beds is the difficulty with coarse-particle fluidization and in spouted beds is the formation of a dead zone. The spout-fluid bed is a hybrid between spouted and fluidized beds that includes two entries for spouting and fluidizing or background velocities.

Within the beds used across many industries, flow pulsation occurs either as an undesirable event or as a technique with useful application. In the literature, this flow pulsation has been investigated in fluidized beds more than in spouted beds; however, a lack of studies on spout-fluid beds is marked.

Zhang and Koksal (2006) employed flow pulsation in a bubbling fluidized bed and noticed an increase in surface-to-bed convective heat transfer of up to 24%. They used a solenoid valve to generate pulse flow with frequencies from 1 to 10 Hz on beds of glass beads and silica sand particles with a range of diameters from 37–700 μm. Higher frequencies and smaller diameters show better results. Using a rotary disk to enter air alternatively among a four-section-base bed, Nitz and Taranto (2007) reported similar performance in drying of beans with lower air consumption in comparison to conventional fluidized beds. They also correlated an empirical equation for their experimental condition to calculate pressure drop as a function of frequency, bed height, and air mean velocity. Hadi, van Ommen, and Coppens (2012) investigated particle mixing in a rectangular-cross-section pulsed fluidized bed. They investigated the hydrodynamics and the rising and bursting of bubbles by analyzing pressure signals. In addition to noticing the higher mixing rate and homogeneity of pulsed fluidization, they found bubble enlargement and gas channeling reduction. Ali et al. (Ali & Asif, 2012; Ali, Asif, & Ajbar, 2014) studied the fluidization of pharmaceutical and paint nano-powders using a pulsed fluidized bed. Although the effect of frequency was not clear, they concluded that pulsation leads to better homogeneity, lower minimum fluidization velocity, and less agglomeration as benefits of flow pulsation.

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Khosravi Bizhaem and Basirat Tabrizi (2013) studied the effect of flow pulsation on hydrodynamics characteristics of fluidized bed. They observed that the bed surface oscillates at the pulsation frequency, and its amplitude increases at lower frequencies. They concluded that flow pulsation generates a higher pressure drop, smaller bubble sizes, and less agglomeration. Saidi, Basirat Tabrizi, Chaichi, and Dehghani (2014) investigated the influence of flow pulsation on classification of dissimilar particles in a fluidized bed. The increased segregation was observed in comparison to steady fluidization. Better performance of the bed and increased participation of particles was concluded as a result of the elimination of dead zones and channel-like structures. Moreover, there have been other experimental efforts on augmenting the flow pulsation to decrease the agglomeration of fine coal (Duan et al., 2015), biomass (Jia et al., 2015), nano-particles (Akhavan, Rahman, Wang, & Rhodes, 2015), and starch (Dacanal, Feltre, Thomazi, & Menegalli, 2016).

The development of computational hardware has given rise to the implementation of numerical methods alongside experimental work. Among various approaches, discrete element method (DEM) and two-fluid model (TFM) are the most common. Early numerical studies on the pulsed fluidized bed go back to Wang and Rhodes (2005a, 2005b), who used DEM to model pulsed fluidization and noticed ordered pressure fluctuations and regular bubble patterns for both sinusoidal and square pulsations. They also found that the formation of regular bubble patterns is caused by the periodical formation of horizontal channel-like structures near the distributor plate. Gui and Fan (2009) studied the influence of pulsation on a bubbling fluidized bed containing an immersed tube using the DEM and large eddy simulation (LES). They observed that the pressure drop, inter-particle forces, and gas-particle forces fluctuated with the same frequency of the imposed pulsation. They indicated that high-frequency pulsations suppressed the fluctuating motion of the particles. Li, Su, Wu, Wang, and Mujumdar (2009) used TFM to study the flow field and bubble characteristics in a 2D pulsed fluidized bed and observed intermittent, resonant, and normal fluidization regimes for different frequencies. Pulsations led to higher expansion ratios and less fluctuations in the bed.

A review of the literature reveals that most experimental and numerical studies on flow pulsation have been performed on fluidized beds. However, studies on pulsed spouted bed are rather scarce, specifically, two experimental and two numerical. Devahastin and Mujumdar (2001) studied in experiments the effect of flow pulsation on the hydrodynamics and mixing characteristics of a spouted bed dryer and observed spouting, transition, and slugging regimes. They reported that flow pulsation led to better performance in terms of the maximum spoutable bed height, solid circulation rate, and mixing. The other experimental investigation by Niamnuy, Kanthamool, and Devahastin (2011) on the hydrodynamics of pulsed spouted bed evidenced higher maximum spoutable bed height than in the steady spouted bed. This finding is related to the reduced radial percolation of upward momentum of the intermittent jet. Using coupled computational fluid dynamics (CFD)–discrete element method (DEM), Saidi, Basirat Tabrizi, Grace, Lim, and Ahmadi (2015) investigated numerically the hydrodynamics of pulsed spouted bed. They found increased particle circulation and upward air momentum for pulsed spouted bed, which leads to better mixing and homogeneity. Further numerical investigation by Saidi, Basirat Tabrizi, Ahmadi, Grace, and Lim (2016) compared steady and pulsed spouted bed with three different waveforms: square, sinusoidal, and triangular. From the view point of mixing, particle flux, and air velocity distributions, the advantages of all waveforms in comparison to steady spouted bed were attained. However, because flow changes were abrupt, the square pulsation enhancement was greater than for sinusoidal and triangular waveforms.

Thus, the focus of the studies on pulsed flow beds has been on fluidized and spouted beds, and more particularly on experimental investigations of fluidized beds. A lack of studies of flow pulsation in spout-fluid beds (SFBs) has prompted a closer look at particle motion in a spout-fluid bed that benefits from flow pulsation. A numerical approach using CFD–DEM has been employed and verified by a steady test case. Fluidizing velocity effect on pressure drop, total height, and particles traversed distance has been sought. Flow pulsation with different frequencies and amplitudes has been tested for fluidizing and spouting entries to model spouted pulsed-fluidized bed (SPFB) and pulsed-spouted fluidized bed (PSFB).

Model description

CFD, based on a modified Navier–Stokes equation, is employed to solve for the gas phase and to provide detailed information of the flow. Newton's second law is used to solve the solid phase motion at the particle scale to provide detailed information on bed hydrodynamics. These equations are coupled through the voidage and fluid-particle interaction force. The governing equations for the gas phase including the effect of local voidage derived from conservation of mass and momentum are as follows:

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g\right)+\nabla\cdot\left(\alpha_g\rho_g\vec{u}_g\right)=0, \tag{1}$$

$$\frac{\partial}{\partial t}\left(\alpha_g\rho_g\vec{u}_g\right)+\nabla\cdot\left(\alpha_g\rho_g\vec{u}_g\vec{u}_g\right)=-\alpha_g\nabla p+\alpha_g\rho_g\vec{g}-\nabla\cdot\bar{\tau}_g-\vec{S}_p, \tag{2}$$

where α_g, ρ_g, $\vec{u}_g$, and p are voidage, density, velocity, and pressure; the stress tensor is given by $\bar{\tau}_g=-\alpha_g\mu_g\left(\nabla\vec{u}_g+(\nabla\vec{u}_g)^{\mathrm{T}}\right)$ and the source term from momentum exchange is given by $\vec{S}_p=\frac{1}{V_{\mathrm{cell}}}\sum_{\forall i\in cell}\frac{V_i\beta}{1-\alpha_g}(\vec{u}_g-\vec{v}_i)$. In these equations, $\vec{u}_g$, V_{cell}, V_i, and $\vec{v}_i$ are gas viscosity, cell volume, particle volume, and particle velocity, respectively. The governing equations for the translational and rotational motion of the solid phase are

$$m_i\frac{d^2\vec{r}_i}{dt^2}=m_i\vec{g}+\frac{V_i\beta}{1-\alpha_g}\left(\vec{u}_g-\vec{v}_i\right)+\sum_j\left(\vec{F}_{\mathrm{cn},ij}+\vec{F}_{\mathrm{ct},ij}\right), \tag{3}$$

$$I_i\frac{d\vec{\omega}_i}{dt}=\sum_j\left(r_i\vec{n}_{ij}\times\vec{F}_{\mathrm{ct},ij}\right), \tag{4}$$

where m_i, $\vec{r}_i$, $\vec{\omega}_i$, I_i, r_i, $\vec{n}_{ij}$, $\vec{F}_{\mathrm{cn},ij}$, and $\vec{F}_{\mathrm{ct},ij}$ are, respectively, particle mass, position, angular velocity, moment of inertia, radius, collision normal unit vector, normal contact force, and tangential contact force. The momentum exchange coefficient (β) is calculated using the Gidaspow empirical correlation (Gidaspow, 1994).

Particle collisions are modeled using a combination of mechanical springs, dashpots, and sliders with specific stiffness, damping coefficient, and friction coefficient. The contact force is calculated as a summation of the elastic and inelastic forces using the spring–damper system. In a sliding situation, the tangential force is taken to equal the friction force. The normal ($\vec{F}_{\mathrm{cn},ij}$) and tangential ($\vec{F}_{\mathrm{ct},ij}$) collision contact forces are defined as

$$\vec{F}_{\mathrm{cn},ij}=-k_n\delta_n^{3/2}\vec{n}_{ij}-\eta_n\vec{v}_{n,ij}, \tag{5}$$

$$\vec{F}_{\mathrm{ct},ij}=\begin{cases}-k_t\vec{\delta}_t-\eta_t\vec{v}_{t,ij} & |\vec{F}_{\mathrm{ct},ij}|\le\lambda|\vec{F}_{\mathrm{cn},ij}|\\ -\lambda|\vec{F}_{\mathrm{cn},ij}|\vec{t}_{ij} & |\vec{F}_{\mathrm{ct},ij}|>\lambda|\vec{F}_{\mathrm{cn},ij}|\end{cases}, \tag{6}$$

where k, η, λ, $\vec{\delta}$, $\vec{v}_{n,ij}$, $\vec{v}_{t,ij}$, $\vec{n}_{ij}$, and $\vec{t}_{ij}$ are the spring stiffness, damping coefficient, friction coefficient, displacement, normal relative velocity, tangential relative velocity, normal direction and tangential direction of collision, respectively. The normal and tangential

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