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Original Research Paper

# Force characteristic of a large dense object in a fluidized bed equipped with an inclined air distributor

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ABSTRACT

Large dense objects are easily stagnated over the distributor during fluidization, having serous influence on bed performance. In this study, three-dimensional modeling of the gas–solid flow in a fluidized bed equipped with an inclined air distributor is conducted by means of two-fluid model to explore the characteristics of the force acting on a stagnant object in bottom bed. Images of the instantaneous particle concentration demonstrate the inhomogeneity of transverse gas–solid flow in bottom bed. The influences of gas velocities on the force fluctuation characteristic for object in various positions of the bottom bed are evaluated. Statistical, spectral and wavelet analysis methods are applied to disclose the time-averaged and instantaneous characteristic of the forces. Results show that with the increasing of gas velocity, the transverse movements of bubbles and particles are both intensified, and the latter is more significant. The dominant frequency of the forces on an object along the inclined direction is 0.3–0.5 Hz, which is smaller than that perpendicular to the distributor of 1.2 Hz.

## 1. Introduction

Simultaneous treatment of dissimilar particles, differing in size, shape and density is normally encountered in a fairly large number of industrial applications of gas–solid fluidization process [1,2]. Many of these processes involve the motion of large objects within the bed, being fuel particles, catalysts, agglomerates, etc. Among them, some objects, especially with large density can easily be captured in the stagnant zones over the distributor, having serous influence on the performance of the bed [3–5].

Several researchers have focused on how to avoid the object being stagnant at the bottom of the bed. Some has proposed the use of different actuators, including vibrating beds [6], pulsed gas flow [7] and advanced distributor designs, such as spiral [8], rotating distributors [5,9] and oriented air caps [3]. However, for large and dense objects, adjusting operating condition such as increasing gas velocity and using actuators both cannot force them to fluidize again. Thus, attentions have been paid on how to discharge them from the bed effectively. Uneven air distribution, such as inclined air distributor and oriented caps induce an internal gas–solid circulation inside the bed, which may drive the large dense objects to the discharging hole [3,10,11]. Cai et al. [12] experimental studied the effect of inclined angle of air distributor on the residence time of a large dense object in a fluidized bed, and they found that with the increasing of the inclined angle, the inhomogeneity of transverse flow in bottom zone of a fluidized bed is enhanced. Thus the force driving the object to the low side of the air distributor increases and the deposition phenomena may be avoided.

The residence time and the motion behaviors of the large dense object within the bottom zone of the bed are dominantly determined by the joint effect of the gas phase and the fine particles in the dense phase. Thus, it is of significant to investigate the force characteristics of the large object in the dense zone of a gas–solid fluidized bed with uneven air distribution. Some researchers have carried out a series of studies on the motion regularity of the immersed objects in fluidized beds [4,13–18]. Sanderson and Rhodes [4] characterized the motion cycles of a single large object in a two-dimensional bed as sinking down from the surface of the bed and rising back again. He et al. [17] studied the force characteristic of a large immersed particle in a fluidized bed under different fluidized velocities using self-designed measurement method and numerical simulation approach. Tsuji et al. [19] conducted a simulation on the floating and sinking motions of a large sphere in a bubbling fluidized bed. In this simulation, it was assumed that a large object consists of fine, dense fictitious particles and the amount of momentum exchange between the fluid and the object

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**Nomenclature**

| | |
|---|---|
| $C$ | Courant number |
| $d$ | diameter, mm |
| $e$ | restitution coefficient |
| $F_{bd}$ | force acting on the object from surrounding gas–solid flow, N |
| $F_p$ | pressure force, N |
| $F_v$ | viscous forces, N |
| $g_0$ | radial distribution function |
| $H$ | bed height, m |
| $L$ | length of the bed cross-section, m |
| $M$ | width of the bed cross-section, m |
| $p$ | pressure, Pa |
| $S\ (x, y, z)$ | object position, mm |
| $v$ | gas velocity, m/s |
| $v_{mf}$ | critical fluidization velocity, m/s |

*Greek letters*

| | |
|---|---|
| $\alpha$ | volume fraction of each phase |
| $\alpha_{p,\max}$ | the maximum particle packing |
| $\beta$ | interphase momentum exchange coefficient, kg/m$^3$ s |
| $\gamma$ | dissipation of energy fluctuation, kg/m s$^3$ |
| $\Delta t$ | time step, s |
| $\Theta$ | granular temperature, m$^2$/s$^2$ |
| $\Gamma_\Theta$ | diffusion coefficient for the energy fluctuation, kg/m s |
| $\lambda_p$ | bulk solids viscosity, Pa s |
| $\mu_g$ | gas viscosity, Pa s |
| $\mu_p$ | shear solids viscosity, Pa s |
| $\theta$ | inclined angle of air distributor, Pa s |
| $\rho$ | density, kg/m$^3$ |
| $\tau$ | stress tensors, Pa |

*Subscripts*

| | |
|---|---|
| $x, y, z, \xi, \eta, \gamma$ | direction |
| g | gas phase |
| p | solid phase |
| o | object |

was calculated from the fine particle. Whereas, the effectiveness of this simulation method has not been widely validated.

Most of the above researchers, however, paid their attention on the vertically motion behavior or the force characteristics of light objects, little has been reported in the literature on transverse motion behavior or transverse forces of a stagnant objects in a fluidized bed. Due to the existence of the inclined air distributor or oriented caps, the transverse gas–solid flow and the transverse forces acting on the stagnant object become significant, which is very different from that of the normal fluidized bed. Therefore, the current study numerically investigates the fluctuation characteristics of the forces acting on a stagnant object in a fluidized bed equipped with an inclined air distributor. At first, the hydrodynamics of the bottom bed is studied, and the emphasis is laid on the transverse gas–solid motions. Then, the influences of gas velocities on the force acting on an object in various positions of the bottom bed are evaluated. The statistical method and the wavelet multi-resolution analysis are conducted to disclose the instantaneous fluctuation characteristic of the forces.

## 2. Modeling

The Eulerian–Eulerian method applied in this study uses temporal and spatial averaging of fluid and particle variables along with principles of mass, momentum and energy conservation to obtain continuum equations for each phase. Details on the derivation of the continuum equations for fluidized beds are provided by Gidaspow [20] and Jackson [21]. The field equations are numerically solved explicitly in time and with a finite difference technique in a staggered grid.

### 2.1. Continuity and momentum equation

The accumulation of mass in each phase is balanced by the convective mass flows:

$$\begin{aligned}&\frac{\partial}{\partial t}(\alpha_g\rho_g) + \nabla\cdot(\alpha_g\rho_g v_g) = 0\\&\frac{\partial}{\partial t}(\alpha_p\rho_p) + \nabla\cdot(\alpha_p\rho_p v_p) = 0\\&\alpha_g + \alpha_p = 1\end{aligned} \tag{1}$$

where $\alpha$, $\rho$ and $v$ are the concentration, density and velocity of each phase. The subscript g and p represents gas phase and particulate phase, respectively. Mass exchanges between the phases are not considered.

The momentum balance for the gas phase is given by the Navier–Stokes equation, modified to include an interphase momentum transfer term:

$$\begin{aligned}&\frac{\partial}{\partial t}(\alpha_g\rho_g v_g) + \nabla\cdot\left(\alpha_g\rho_g v_g v_g\right) = -\alpha_g\nabla p + \nabla\tau_g + \alpha_g\rho_g g + \beta(v_p - v_g)\\&\frac{\partial}{\partial t}\left(\alpha_p\rho_p v_p\right) + \nabla\cdot(\alpha_p\rho_p v_p v_p) = -\alpha_p\nabla p - \nabla p_p + \nabla\tau_p + \alpha_p\rho_p g + \beta(v_g - v_p)\end{aligned} \tag{2}$$

where $\tau_g$ is the stress tensor for the gas phase, and is given by

$$\tau_g = \alpha_g\mu_g\left(\nabla v_g + \nabla v_g^T\right) - \frac{2}{3}\alpha_g\mu_g(\nabla v_g)I \tag{3}$$

where $\mu_g$ is the gas viscosity. $\tau_p$ is the stress tensor for the particle phase, and can be calculated as

$$\tau_p = \alpha_p\mu_p(\nabla v_p + \nabla v_p^T) - \alpha_p(\lambda_p - \frac{2}{3}\mu_p)(\nabla v_g)I \tag{4}$$

where $p_p$, $\lambda_p$ and $\mu_p$ are the solids pressure, bulk solids viscosity and shear solids viscosity, respectively. And they can be calculated from kinetic theory of granular flow discussed below.

### 2.2. Kinetic theory of granular flow

There are two possible mechanisms inducing the fluctuations of particle velocity: interparticle collisions and particle interactions with turbulent fluctuations in the gas phases. Interparticle collisions play a crucial role in sufficiently dense suspensions. Equivalent to the thermodynamic temperature for gases, the granular temperature can be introduced as a measure for the energy of the fluctuating velocity of the particles. The granular temperature, $\Theta$ is defined as: $\Theta = c^2/3$, where $c$ is the particle fluctuating velocity. The equation of conservation of solids fluctuating energy is as follows [20]

$$\frac{3}{2}\left[\frac{\partial(\alpha_p\rho_p\Theta)}{\partial t} + \nabla(\alpha_p\rho_p v_p\Theta)\right] = \left(-p_p\bar{\bar{I}} + \bar{\bar{\tau}}_p\right) : \nabla v_p + \nabla(\Gamma_\Theta\nabla\Theta) - \gamma \tag{5}$$