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Granular temperature and rotational characteristic analysis of a gas–solid bubbling fluidized bed under different gravities using discrete hard sphere model

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ABSTRACT

A gas–solid bubbling fluidized bed was analyzed by using a discrete hard sphere particle model (DPM). Simulation results were validated by matching them to the results of the previous study. Particle translational and rotational characteristics were investigated in terms of gravities to find out their influences on the particle behaviors. The gravity did not significantly affect the particle macro-scale characteristics, such as particle translational velocity and rotational velocity, but acted an important role in particle micro-scale characteristics like granular temperatures. Particularly, the change of gravity affected the change of the bubble behavior and the particles' pulsation movement, which could lead to the transformation of the overall fluidized state.

1. Introduction

Fluidized bed is one of the most widely used dense gas–solid two phase systems. With long period developing, it has been applied to chemical industry, clean-energy application, agriculture, mining industry etc. As a wide-spread and well-adapting particle system, the investigation of fluidized bed under different gravities is of great significance. Not only because the potential application of fluidized bed is not far to see, but also the gravity does play an important role in particle behaviors.

Liu et al. [1] simulated the hydrodynamic behavior of dense gas–particle flows in gas-fluidization reactor by using a Euler–Euler two-fluid model including the influence of gravity. A unified second-order-moment gas–particle two-phase turbulent model incorporated with kinetic theory of granular flows was developed to study the particle dispersion behavior of dense gas–particle flows by Pan et al. [2]. A Euler–Euler two-fluid model based on the second-order-moment closure approach was proposed by Liu et al. [3] to investigate the dense gas–particle turbulence flows under microgravity space environments.

For the gas–solid two-phase flow, two simulation methods have been applied: Euler–Euler model and Euler–Lagrange model. Euler–Euler model has been widely used with an advantage in simulating large scale system [4–8]. The limitation of Euler–Euler model is that it cannot go through all the details of particle behavior, especially for the particle–particle collisions. Euler–Lagrange model has the opposite characteristics. It can give most of the dynamic characteristics of particles, but it can only be applied to small scale systems [9]. With the current development of computers, Euler–Lagrange model has become popular among researchers with many successes in some areas, such as bubbling fluidized bed [10,11], spouted bed [12,13], downer [14] and riser [15].

Detailed particle dynamic characteristics lead to a stirring of interest in particles' turbulent characteristics, because it reveals the intensity of particle fluctuations in a fluidized bed. Godlieb et al. [16] obtained the particles' granular temperature by using the DPM model. Peng et al. [17] investigated the granular temperature in a bubbling fluidized bed. Wang et al. [18] used a DSMC method to predict the granular temperature in a riser. Holland et al. [19] performed an experiment to obtain the anisotropic granular temperature in fluidized beds. Wildman and Huntley [20] presented a review of the development of techniques available for measuring the granular temperature in 3-D dry granular flows. Though some progress in studying particle dynamic characteristics has been made, the studies on particle rotational characteristics are still lacking.

In this work, a discrete hard sphere particle model (DPM) is applied to numerically study the distributions of particle and bubble granular temperature in a bubbling fluidized bed. Various gravities are applied to find out their influences on the particle and bubble granular temperatures.

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Nomenclature

d_p	particle diameter (m)
e_n	normal coefficient of restitution (–)
$\mathbf{g}$	gravity (m·s^{-2})
$\mathbf{I}_a$	moment of inertia (kg·m^2)
m_a	particle mass (kg)
m	the number of frames that are averaged in time (–)
n	particle number in a unit volume (–)
N	fluidization number (–)
N_p	number of all the particles (–)
P	pressure (Pa)
r	particle position (m)
$\mathbf{r}_a$	particle position vector of particle (m)
Re	Reynolds number (–)
t	time (s)
Δt	time step (s)
T_a	torque (N·m)
$\boldsymbol{u}_g$	gas phase velocity (m·s^{-1})
u_{sp}	superficial gas velocity (m·s^{-1})
$\mathbf{v}_a$	particle velocity vector (m·s^{-1})
$\boldsymbol{v}_p$(r,t)	instantaneous velocity of particle (m·s^{-1})
V	fluid cell volume (m^3)
V_a	particle volume (m^3)

Greek symbols

β	interphase momentum exchange coefficient (kg·m^{-3}·s^{-1})
β_0	tangential restitution coefficient (–)
ε_g	gas phase void fraction (–)
$\theta_{p,tran}$	particle translational granular temperature (m^2·s^{-2})
θ_b	bubble granular temperature (m^2·s^{-2})
$\theta_{p,rot}$	particle rotational granular temperature (rad^2·s^{-2})
μ_g	gas phase shear viscosity (Pa·s)
μ	friction coefficient (–)
ρ_g	gas phase density (kg·m^{-3})
ρ_p	solid phase density (kg·m^{-3})
$\boldsymbol{\tau}_g$	gas-phase stress tensor (Pa)
ω_p	particle rotational velocity (rad·s^{-1})
Ω_p	particle rotational acceleration (rad·s^{-2})

2. Numerical method

2.1. Simulation model

2.1.1. Description of the solid phase

The hard-sphere discrete particle model was originally proposed by Hoomans [21]. In DPM simulation, particles are assumed to be rigid spheres, and collisions among particles are considered as binary, instantaneous, impulsive events.

The velocity of every individual particle can be calculated from Newton's second law, containing forces due to the pressure gradient, drag and gravitation:

$$m_a \frac{d^2\mathbf{r}_a}{dt^2} = \frac{V_a\beta}{1-\varepsilon}(\mathbf{u}-\mathbf{v}_a) - V_a\nabla P + m_a\mathbf{g} \tag{1}$$

$$I_a\mathbf{\Omega}_a = I_a\frac{d\boldsymbol{\omega}_a}{dt} = \mathbf{T}_a. \tag{2}$$

In this model, it is assumed that the interaction forces are impulsive and therefore all other finite forces are negligible during collisions.

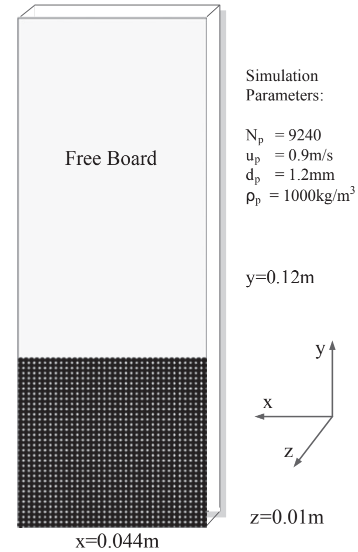

Fig. 1. Schematic illustration of the dimensions and initial setup of the bubbling bed.

2.1.2. Description of the gas phase

The gas phase is modeled by the volume-averaged Navier–Stokes equations:

$$\frac{\partial\left(\varepsilon_g\rho_g\right)}{\partial t} + \nabla\cdot\left(\varepsilon_g\rho_g\mathbf{u}_g\right) = 0 \tag{3}$$

$$\frac{\partial\left(\varepsilon_g\rho_g\mathbf{u}_g\right)}{\partial t} + \nabla\cdot\left(\varepsilon_g\rho_g\mathbf{u}_g\mathbf{u}_g\right) = -\varepsilon_g\nabla P - \mathbf{S}_p - \nabla\cdot\left(\varepsilon_g\boldsymbol{\tau}_g\right) + \varepsilon_g\rho_g\mathbf{g}. \tag{4}$$

There is a source term $\mathbf{S}_p$, defined as:

$$\mathbf{S}_p = \frac{1}{V}\int\sum_{a=0}^{N_p}\frac{\beta V_a}{1-\varepsilon_g}\left(\mathbf{u}_g - \mathbf{v}_a\right)\delta(\mathbf{r}-\mathbf{r}_a)dV. \tag{5}$$

The distribution–function δ distributes the reaction force of the particles exerted on the gas phase to the velocity nodes on a (staggered) Eulerian grid, and β is the interphase momentum exchange coefficient.

Table 1
Simulation parameters.

Parameter	Value	Unit
Particle diameter, d_p	1.2	(mm)
Particle density, ρ_p	1000	(kg/m^3)
Normal restitution coefficient, e_n	0.97	(–)
Tangential restitution coefficient, β_0	0.33	(–)
Friction coefficient, μ	0.10	(–)
Time step, Δt	1×10^{-5}	(s)
Bed width, W	0.044	(m)
Bed depth, D	0.01	(m)
Bed height, H	0.12	(m)
CFD grid number, N_x	12	(–)
CFD grid number, N_y	24	(–)
CFD grid number, N_z	1	(–)
Shear viscosity of gas, μ_g	1.8×10^{-5}	(Pas)
Gas temperature, T	298.15 K	(K)
Pressure, P	1.2×10^5	(Pa)
Superficial gas velocity, u_{sp}	0.9	(m/s)
Number of particles, N_p	9240	(–)