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An Eulerian-Lagrangian Modeling of Fluidized Bed

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Abstract: The particle motions in a fluidized bed were numerically simulated using a Eulerian-Lagrangian model. The solid phase was modelled via the Discrete Element Method (DEM) while the hydrodynamic model of the fluid phase was based on the volume-averaged Navier-Stokes equations. A fluid density-based buoyancy (FDB) model was adopted to calculate the solid-fluid interaction force. In this paper, the complex 'four way coupled' interaction as proposed by Elghobashi in 1991 was modelled, namely the dominant effect of gas phase on the dispersed particles, the back influence of the particle phase on the gas phase, and interactions between particles such as collision, agglomeration and break-up. A stable succession of bubble formation and disappearance was captured. Obtained pressure drop and interparticle contact number had a good agreement with those reported in previous reference.

Key words: Eulerian-Lagrangian, DEM, FDB, Fluidized bed

1 Introduction

Over the past decades, numerical simulation has been widely adopted as a research, design or development tool both in the industry and academia due to the dramatic increase in computer processor capacity. Gas-particle flow in fluidization can be found in many industries and has been the subject of intensive research. Eulerian-Lagrangian model plays an important role in the development of a comprehensive understanding of the fundamentals of this phenomenon. In the Eulerian-Lagrangian models, the governing equations of surrounding fluid are solved prior to the calculation of particle motion in each computational time-step. Particle-fluid interaction force is obtained based on the empirical fit[2]. Then, the Lagrangian methodologies such as DEM[3] can be used to track the particle motion. Since the pioneering work of Tsuji[4], this kind of 'Continuum+Particle' model has been the subject of many studies [5-11] on fluidized bed simulation. Firstly, two formulations of the fluid governing equation were proposed in[12], namely the so-called Model A: Pressure Gradient Force (PGF) and Model B: Fluid Density Model (FDB). Based on the research of Kafui et al[5], Model A showed the best agreement with pressure drop-superficial gas velocity trends and minimum fluidization velocities predicted by empirical correlations. However,

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Feng et al[6] made an assessment of Model A and B by comparing the physical experiments, by means of the results he argued that the model B was favored. Nowadays, both the models were adopted by researchers. Examples of Model A can be found in: Hoomans et al[7] and Olaofe et al[8] investigated the bubble formation in 2D gas-fluidized bed. Xiang et al[9] simulated the particle motion in vibrated fluidized beds. Examples of Model B can be found in: Feng at al[10] investigated the particle segregation and mixtures in fluidized bed. Zhou et al[11] studied heat transfer in fluid bed reactors. In the current study, the continuum modeling proposed by Anderson and Jackson [13] was employed to evaluate the gas motion, Model B (FDB)[12] was adopted to approach the interaction force between the gas phase and the solid particles, while DEM[3] was used to describe the trajectory of particles and interactions between the particles or between

2 Model equations

2.1 Eulerian equations of the gas phase

The continuity and momentum equations in the fluid are based on local mean variables as derived by Anderson and Jackson[13].

$$\frac{\partial(\varepsilon\rho_f)}{\partial t}+\nabla\cdot(\varepsilon\rho_f u)=0 \tag{1}$$

$$\frac{\partial(\varepsilon\rho_f u)}{\partial t}+\nabla\cdot(\varepsilon\rho_f u\otimes u)=-\nabla p+\nabla\cdot\varepsilon\tau_f+(1-\varepsilon)\nabla p-n_e\varepsilon f_{di}+\varepsilon\rho_f g \tag{2}$$

where u and ρ_f are the fluid velocity and density, respectively, ε is the porosity, p is the fluid pressure, τ_f is the viscous stress, g is the gravitational acceleration, n_e is the number of particles in one fluid cell and f_{di} is the drag force. More detailed formulations are referred to our previous works[14]. Note that $(1-\varepsilon)\nabla p-n_e\varepsilon f_{di}+\varepsilon\rho_f g$ in Eq.(2) will be regarded as a source term when solving the fluid equations, the way we used to calculssate the interaction force is called the fluid density-based buoyancy model (FDB)[12].

2.2 DEM modeling of the interaction between moving particles

The Discrete Element Method (proposed by Cundall[3]) was used to account for the interactions between particles and the walls. When taking into account all the forces acting on each particle, the dynamic equations of the discrete element read:

$$\begin{cases} ma=F_c+f_{fpi}+mg \\ I\dfrac{\partial^2\theta}{\partial t^2}=\tau \end{cases} \tag{3}$$

where m and I are respectively the mass and the moment of inertia of a particle, θ is the angular position, g is the gravitational acceleration, τ is torque, F_c is the contact force and f_{fpi} is the fluid-solid interaction force.

3 Numerical illustrations

In this paper, we used finite-volume SIMPLER algorithm[15] with staggered grid to solve the

Navier-Stokes equations, where the power-law upwinding scheme was used for the convection term with central difference scheme for the diffusion term, explicit calculations of fluid velocity components was adopted when solving the temporal term. The simulations were performed under the same conditions with those used by Kafui et al[5], as listed in Table 1. The initial packing was obtained by random generation of particles without overlap in the bed, followed by a gravitational settling process for 2 s with the initial porosity 0.555. Gas was then injected into the bed from the bottom uniformly (3.0 m/s). The contact forces between particles or between particles and walls can be divided in normal and tangential forces. A well tested DEM code[16] was adopted for the calculation of the incremental forces and torques in each time step, where the theory of Hertz[17] was used in modeling the normal force-displacement relationship while the theory of Mindlin and Deresiewicz[18] was employed for the tangential force-displacement calculations.

Table 1. Parameters and bed geometry used for fluidized bed simulation

Solid phase		Gas phase	
Number of particles	2400	Viscosity/ $kg \cdot m^{-1} \cdot s^{-1}$	1.8×10^{-5}
Density /$kg \cdot m^{-3}$	2700	Density/ $kg \cdot m^{-3}$	1.205
Young's Module /$N \cdot m^{-2}$	6.895×10^{10}	Bed height /m	0.7
Poisson ratio / $N \cdot m^{-2}$	0.33	Bed width/ m	0.15
Friction coefficient	0.33	Cell height /m	0.01
Diameter /m	0.004	Cell width /m	0.01

4 Results and discussion

Fig.1 illustrates the initial response of the bed to the introduction of the gas. The magnitude of bed expansions shown in Fig.1 are higher than those of Fig.4(b) in the paper of Kafui et al[5]. That's because of that the initial velocity of the injected gas was 0.3 m/s in the simulation of Kafui at al and then increased in steps to 3.0 m/s whereas the velocity of the injected gas in current study is constantly 3.0 m/s though the initial porosity is a little higher than that in[5]. Typical flow patterns during the fluidisation are shown in Fig.2, it can be seen that a stable succession of bubble formation and disappearance is established. The bubbles travel at vertical speeds, some of them are carried all the way to the top of the bed while others are dissipated in the bed especially when they encounter falling particles. The degree of mixing attained after 23 s in this monodispersed particle system is considerable. In both Fig.1 and 2, a defluidized layer can be found. In this layer, the particles are entrapped by surrounding jetsam particles and cannot move upward. The succession can be also observed from the pressure drop across the bed and the number of interparticle contacts profile as shown in Fig.3. In our simulation, the mean pressure drops is 3.48 kPa, which is a little lower than the bed weigh pressure of 3.56 kPa, the pressure fluctuates around mean pressure drop with succession of the expansions. And because a higher injection velocity is adopted in this study, the contact number is obviously lower than that in[5]. Lower interparticle contact number stands for more drastical fluidisation.

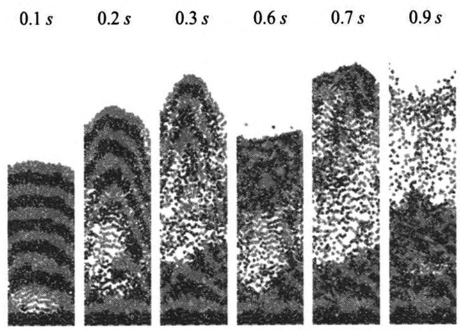

Fig.1 The initial response of the bed to the introduction of gas injection at velocity 3.0 m/s

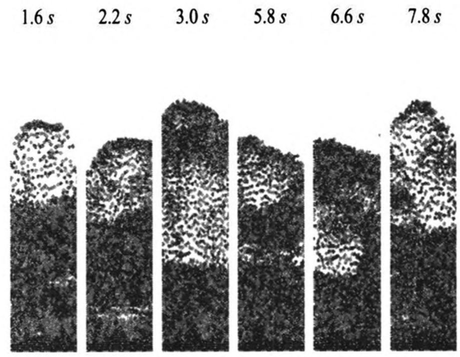

Fig.2 Typical solid flow pattern at velocity 3.0 m/s

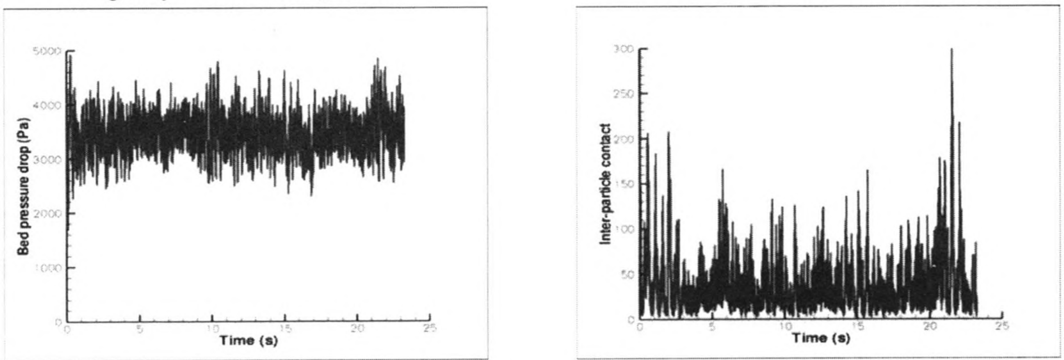

Fig.3 (a) Variation of the bed pressure drop with time; (b) Interparticle contact fluctuation during simulation

5 Concluding remarks

In this paper, an Eulerian-Lagrangian model was applied to investigate a fluidized bed. Numerical simulations were carried out and the characteristic of fluidized bed was observed. A stable succession of bubble formation and disappearance was captured. Obtained pressure drop and contact number have a good agreement with those reported in previous reference. The simulation demonstrated the capability of the current coupled scheme.

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Nomenclature			
a	acceleration of the particle, m/s^2	f_{di}	drag force on a single particle, N
f_{fpi}	interaction force between fluid and a single particle, N	F_c	contact forces between particles, N
g	acceleration of gravity, m/s^2	I	moment of inertia, kg·m^2
m	mass of the particle, kg	n_e	number of particles in one fluid element
p	fluid pressure, Pa	u	fluid velocity, m/s
Greek letters			
θ	angular position, rad	ε	porosity
ρ_f	density of fluid, kg/m^3	τ_f	the viscous stress, Pa
τ	the torque, N·m		