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Parametric study for MP-PIC simulation of bubbling fluidized beds with Geldart A particles

Meiyan Feng [a], Fei Li [a,*], Wei Wang [a,b], Jinghai Li [a,b]

[a] State Key Laboratory of Multi-phase Complex Systems, Institute of Process Engineering, Chinese Academy of Sciences, Beijing 100190, PR China
[b] University of Chinese Academy of Sciences, Beijing 100490, PR China

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ABSTRACT

This is a parametric study for multi-phase particle in cell (MP-PIC) simulation of bubbling fluidized beds with Geldart A particles using the open source MFIX program. The main parameters have been studied including drag models, grid resolution and number of particles per parcel (PPP). And the calculated axial/radial solid distribution and bed height are compared with the experimental data for validation. It is shown that the drag model can significantly affect the calculation results of bubbling fluidized bed with Geldart A particles. Specifically, the Energy Minimization Multi-scale (EMMS) bubbling drag model can predict right bubbling phenomenon and also improve the accuracy compared to the homogeneous drag model. Bubble analysis shows that there exists a stable average bubble diameter when the bed becomes stable. The average bubble circularities are about 0.5 for the two bubbling bed studied in this work, even though they have different average bubble diameter. Parameter analysis shows that the accuracy of the calculated results improves with decreasing grid size or PPP. There exists a threshold value for grid size/PPP, below which, grid/PPP independent result can be obtained. The PPP plays the similar role to grid resolution in MP-PIC simulation.

1. Introduction

MP-PIC method was proposed by Andrews and O'Rourke [1] originally in 1996. For the fluid phase, it is described with Eulerian method; while for the particle phase, the method similar to the coarse-grained discrete phase model (DPM) approach was used. In this method, "parcel" is on behalf of a group of particles with the same size, speed and density, and the Newton's laws are used to track each "parcel" instead of single particles. So the calculation loading is greatly reduced. This is a great advantage for the MP-PIC method, especially in the calculation of large-scale systems. The method does not track interparticle collision directly, but take into account this effect through solid-phase normal stress [2, 3]. All these attractive advantages make MP-PIC suitable for simulation of large scale gas-solid flow applications [4]. MP-PIC method was used in 2D/3D gas-solid two phase flow simulation by Snider [2] for the first time. And after that, MP-PIC was widely used in fluidization simulations, for example, bubbling fluidized bed [5–7], fast fluidized bed [8–10] and a lot other industrial fluidized bed applications.

Drag model is an important parameter in simulation of bubbling fluidized beds [11–16]. Bubbling fluidized bed flows are characterized with gas bubbles which are also known as meso-scale structures, and the bubbles lead to heterogeneous solid distributions in the beds. So it is necessary to account for the effects of bubbles in bubbling bed simulations. Currently, there are mainly two types of drag models, namely, the homogeneous drag model [13, 14, 17–19] and the heterogeneous drag model [20–26]. Generally the heterogeneous drag models account for heterogeneous solid distribution due to meso-scale structure while homogeneous drag models assume homogeneous solid distribution.

Liang et al. [7] simulated a pseudo-2D bubbling fluidized bed with Geldart B particles by using Barracuda® (a software for MP-PIC method), and the results showed that the currently available adjusting measures (say, time step, mesh size and parcel number, drag model, solid volume fraction at close packing, gas turbulence model), had little effects in the simulation results except for the near-wall mesh refinement. They had just tested the homogeneous drag models [17, 19, 27, 28]. Pugsley et al. [6] investigated the capability of Barracuda® for simulating bubbling bed flows with Geldart A particles, and the results of bubble properties showed acceptable accuracy without modifying the homogeneous drag force or other constitutive relationships in the model. It should also be noted that McKeen & Pugsley [29] showed that the homogeneous drag force coefficient had to be multiplied by a scaling factor less than 1 to obtain the reasonable bed expansion height in simulating bubbling fluidized bed with two-fluid model. Chen et al. [10] simulated CFB riser with Geldart A and Geldart B particles by using Barracuda®. The results indicated that the Wen-Yu/Ergun drag model overestimated the momentum transfer. All the above reports

* Corresponding author.
E-mail address: lifei@ipe.ac.cn (F. Li).

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show that the simulations results calculated with homogeneous drag model arouse controversy in MP-PIC method. Because there exist heterogeneous structures in fluidizations, it is necessary to account for the heterogeneous drag model in MP-PIC method in simulating bubbling fluidized beds [30, 31].

EMMS drag model is one of the heterogeneous drag models. It was developed based on meso-scale structure analysis [20, 32, 33]. In this model, the non-uniform flow is separated into different scales. In details, the gas-solid interaction is decomposed into the interactions between single particles and fluid (micro-scale effect) in both the interior of particle-rich dense phase and the particle-lean dilute phase, and the interaction between dilute phase and dense phase (meso-scale effect). Finally, the drag forces at different scales are summed to obtain the heterogeneous drag force. Recently, a structure-dependent energy dissipation analysis [34] helped better understanding of the EMMS stability condition and drag.

The EMMS drag model was widely used in two-fluid model (TFM) to simulate fluidizations [35–39]. Li et al. [40] introduced the EMMS drag in MP-PIC method and proved that MP-PIC combined with the EMMS drag model can successfully simulate the flow behavior in CFB risers. It can predict not only the macroscopically bottom-dense and top-dilute axial solid distribution as well as the so-called core-annular radial distribution, but also the meso-scale phenomena of particle aggregation. However, the applicability of the EMMS drag in simulation of bubbling fluidized beds has not been studied yet.

In addition, some basic issues in MP-PIC calculations, such as the impacts of the grid resolution and the number of particles per parcel (PPP) on the simulation are seldom studied in the literature. In this paper, the factors affecting bubbling fluidized bed simulations including drag models, grid resolution and PPP will be studied in the frame of MP-PIC method. Two of the drag models including the homogeneous drag [13] and the heterogeneous EMMS drag are used. The simulation results are compared with the experimental data for validation.

2. Model description

2.1. MP-PIC method

MP-PIC is a typical Euler-Lagrange method. The Navier-Stokes (N-S) equations are used to describe the movement of the gas phase, while Newton's second law is used to describe the motion of particle phase. The typical gas-solid equations are listed below [2].

For the gas phase, the continuity and the momentum equations are as follows:

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

$$\frac{\partial}{\partial t}\left(\varepsilon_g \rho_g \vec{u}_g\right) + \nabla \cdot \left(\varepsilon_g \rho_g \vec{u}_g \vec{u}_g\right) = -\varepsilon_g \nabla p + \nabla \cdot \bar{\bar{\tau}}_g + \varepsilon_g \rho_g \vec{g} - \sum_{p=1}^{n_T} n_p \frac{V_p}{V_c} \beta_p \left(\vec{U}_g\left(\vec{x}_p\right) - \vec{U}_p\right) \tag{2}$$

Here, the subscript g represents the gas phase; ε_g is the gas volume fraction; ρ_g is the gas density; $\vec{u}_g$ is the gas phase velocity at cell center; p is the gas pressure; $\bar{\bar{\tau}}_g$ is the gas phase stress tensor; n_T is the parcel number in fluid cell; n_p is the number of particles per parcel; V_p is the particle volume and V_c is the fluid cell volume. β_p is the drag coefficient; $\vec{U}_g(\vec{x}_p)$ is the gas velocity at parcel location; $\vec{x}_p$ is the parcel location; $\vec{U}_p$ is the parcel velocity.

For the particle phase, the equations of motion are as follows:

$$\frac{d\vec{x}_p}{dt} = \vec{U}_p \tag{3}$$

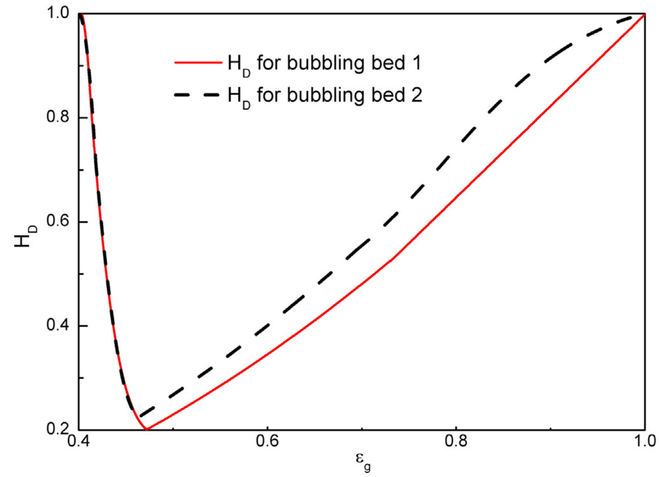

Fig. 1. H_D calculated with EMMS/bubbling drag model for two bubbling fluidized beds (bubbling bed 1: $U_g = 0.1$ m/s, $\rho_g = 1.225$ kg/m^3, $\mu = 1.8 * 10^{-5}$ Pa·s, $\rho_p = 1500$ kg/m^3, $d_p = 7.5 * 10^{-5}$ m; bubbling bed 2: $U_g = 0.06$ m/s, $\rho_g = 1.225$ kg/m^3, $\mu = 1.7894 * 10^{-5}$ Pa·s, $\rho_p = 1780$ kg/m^3, $d_p = 6.5 * 10^{-5}$ m).

$$\frac{d\vec{U}_p}{dt} = -\frac{\nabla p}{\rho_s} + \vec{g} + \frac{\beta_p}{\rho_s}\left(\vec{U}_g\left(\vec{x}_p\right) - \vec{U}_p\right) + F_c \tag{4}$$

Here, F_c represents the interaction force between particles. For traditional Discrete Element Methods (DEM), the collisions between particles need to be tracked to calculate F_c, which requires that the time step of equation for particles is small enough and needs real-time information to calculate the distance between a pair of particles in order to determine whether they collide or not. So the DEM method requires a lot of computing resources and time. For the gas-solid flow of industrial installations or large scale laboratory device, the DEM method is almost impossible to be used.

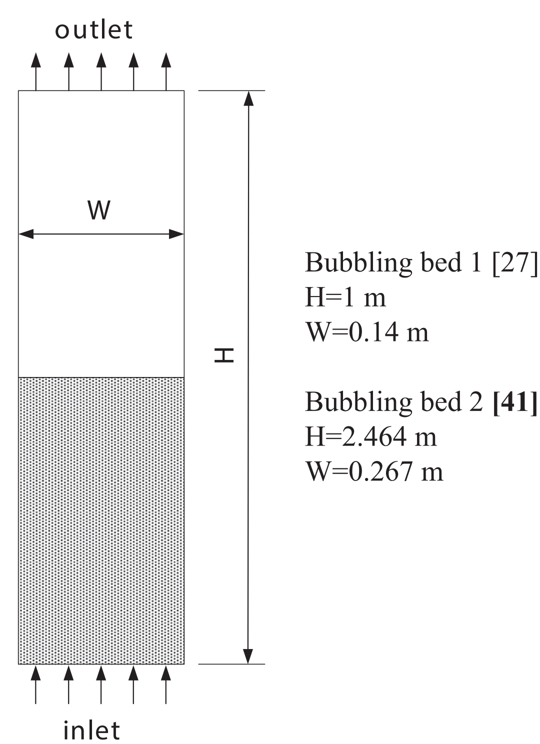

Fig. 2. 2D geometry of the bubbling beds (H: reactor height; W: reactor width).