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A lattice Boltzmann method for particle-fluid two-phase flow

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HIGHLIGHTS

- A new LBM scheme (TF-LBM) solving equations of fluid phase in two-fluid model.
- TF-LBM calculates at the level of TFM, favoring large-scale simulation.
- Combination of discrete particle method and TF-LBM.

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ABSTRACT

A two-fluid lattice Boltzmann method (TF-LBM) is proposed for simulation of particle-fluid flows. The fluid phase is solved by using a modified LBM scheme, which combines the He–Shan–Doolen and the Cheng–Li schemes and, accordingly, restores to the fluid phase equations of the two-fluid model (TFM) by adding additional source terms. While for the sake of simplicity, the motion of particle phase is tracked by following the hard-sphere discrete particle model (DPM). Three test cases, including solid–liquid sedimentation, solo particle sedimentation in air and air–solid two-phase flow in a vertical pipe, are simulated with this new method. The results are compared with previous literature results and experimental data, showing fair agreement.

1. Introduction

Particle-fluid two-phase flow is characterized with nonlinear, non-equilibrium phenomena and multi-scale dynamic structures. To study its complex behavior, various computational fluid dynamics (CFD) methods have been proposed, such as the two-fluid model (TFM) (Anderson and Jackson, 1967; Gidaspow, 1994), discrete particle model (DPM) (Goldschmidt et al., 2004; Tsuji et al., 1998) and the lattice Boltzmann method (LBM), in which LBM has been rapidly developed (Benzi et al., 1992; Chen and Doolen, 1998; He and Luo, 1997; Higuera et al., 1989; Succi, 2001; Succi et al., 1993; Tang et al., 2005) with its merits of natural parallelization and easy dealing with complicated boundaries.

LBM has been applied successfully in simulating many problems, especially for single phase flows. In recent years, some LBM-based multiphase models have also been proposed, including the Eulerian–Eulerian approach (such as the color model (Gunstensen et al., 1991; Tolke et al., 2002), the pseudopotential model (Sbragaglia et al., 2007; Shan and Chen, 1993, 1994), the free-energy model (Swift et al., 1995) and so on (Inamuro et al., 2002)) and the Eulerian–Lagrangian approach (Iglberger et al., 2008; Ladd, 1994; Wang et al., 2010a). However, most of these multiphase models were presented for small-scale simulation at the level of individual particles, and hence, not suitable for large-scale simulation of industrial multiphase reactors.

TFM is an Eulerian–Eulerian method which treats both the fluid and the particle phases as fully interpenetrating continua. It describes the collective behavior of large amount of particles at a level much coarser than individual particles, and hence demands less computational capacity. Thus, TFM is widely accepted to be suitable for industrial scale simulations (Gidaspow, 1994).

To realize fast simulation of industrial two-phase flow, Sankaranarayanan and Sundaresan (2008) and Wang and Wang (2005) have tried to combine the advantages of both LBM and TFM by using LBM to solve the whole set of TFM equations. It should be noted that the original LBM was proposed mainly to solve the Navier–Stokes (N–S) equations. The fluid phase equations of TFM differ from the N–S equation in both mass and momentum

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equations. By introducing the volume fraction of fluid phase and the interphase drag force in the momentum equations, Sankaranarayanan and Sundaresan (2008) modified the external force term of LBM, while Wang and Wang (2005) added a correction factor to the pressure gradient in LBM equations. The two-phase densities used in these two lattice Boltzmann schemes are both partial densities, i.e. $\varepsilon_k \rho_k$, where ε_k refers to the volume fraction of phase k, and ρ_k its density. Compared to the use of phase density, this makes the construction of the scheme easier in mathematics. However, in a typical gas–solid riser flow, the variation of solid volume fraction may range from 0 to $1-\varepsilon_{mf}$, where ε_{mf} is the minimum fluidization void fraction. Such a big variation may violate the assumption of the incompressible or weakly compressible fluid in LB scheme.

If one uses the phase density instead, the main problem to be solved is the source terms encountered in the continuity and the momentum equations, owing to the difference between TFM and N–S equations. There are several methods widely cited in literature to deal with source terms (Guo et al., 2002a; He et al., 1998; Ladd and Verberg, 2001; Luo, 1998; Shan and Doolen, 1995; Shan and Chen, 1993). As analyzed in Guo et al. (2002a), among those methods, the He–Shan–Doolen scheme (He et al., 1998) and the Guo–Zheng–Shi scheme (Guo et al., 2002a) exactly restore the N–S equations of momentum with extra terms added in LBM. However, how to deal with additional source terms in the continuity equation is not addressed in these literatures. Recently, Cheng and Li (2008) proposed a new scheme to introduce unsteady, non-uniform source terms into LBM and they found it allows adding an arbitrary source term to the continuity equation besides introducing unsteady and non-uniform body forces into momentum equations. Both their multi-scale analysis and simulation results show that this new scheme can guarantee the accuracy within incompressible limit. However, the complete use of this new scheme is implicit and needs iterations.

Both the fluid and the particle phases can be resolved based on the continuum equations of TFM, as were the cases in Sankaranarayanan and Sundaresan (2008) and Wang and Wang (2005). On the other hand, various discrete simulation methods, such as DPM, are good alternatives for describing motion of particles, where the Lagrangian trajectories of particles are determined by following Newton's laws of motion as well as collisions rules (Hoomans et al., 1996; Kawaguchi et al., 1998; Tsuji et al., 1993, 1984). In particular, the rapid development of coarse-grained approaches such as the multiphase particle-in-cell (MPPIC) model (Snider, 2001; Snider et al., 1998) has attracted much research interest, in the sense that the huge amount of particles can be replaced with much less parcels so that the computational loading is even lower than that of conventional TFM simulations. In addition, the massively parallel computing with GPU technology also helps to boost the development of Lagrangian methods (Chen et al., 2009; Xiong et al., 2012). As shown by Xiong et al. (2012), LBM shows a strong scalability of multi-GPU implementation: even with 600 GPUs, the computing capacity still has a linear relationship with the number of GPUs. This makes that LBM has a better performance in large scale simulation than the conventional CFD method. And this is why we tend to choose LBM to realize fast simulation of industrial two-phase flow reactors.

This work aims at fast simulation of large-scale particle-fluid systems. To this end, we propose a two-fluid lattice Boltzmann method (TF-LBM) featuring LBM solution at the level of TFM. To be consistent with TFM in terms of both continuity and momentum equations and, at the same time, to be explicit in time for the sake of parallel computing, we combine and modify the LBM schemes of Cheng–Li (Cheng and Li, 2008) and He–Shan–Doolen (He et al., 1998) to solve the fluid phase equations of TFM; whereas the particle phase is resolved with DPM for the sake of easy implementation as a first attempt. It should be noted that the other discrete simulation methods for particles, such as MP-PIC, can also be easily implemented under the same framework.

The article is organized as follows: First, the detail of the TF-LBM scheme is presented in Section 2; then, for validation purposes, three typical cases, including solid–liquid sedimentation, solo particle sedimentation in air and air–solid two-phase flow in a vertical pipe, are simulated with this new scheme in Section 3; finally, the main conclusion is presented.

2. Model

2.1. LBM for fluid phase

The TFM equations for the fluid phase have the following form (Gidaspow, 1994):

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

$$\frac{\partial}{\partial t}(\varepsilon\rho_f\mathbf{u})+\nabla\cdot(\varepsilon\rho_f\mathbf{u}\mathbf{u})=-\varepsilon\nabla p+\nabla\cdot(\varepsilon\mathbf{T})+\mathbf{F}_d+\varepsilon\rho_f\mathbf{g} \tag{2}$$

Here, ε, ρ_f and p denote the void fraction, the fluid density and the fluid pressure, respectively; $\mathbf{u}$ and $\mathbf{T}$ denote the fluid velocity and the fluid stress tensor, which is calculated by $\mathbf{T}=\mu_f[\nabla\mathbf{u}+(\nabla\mathbf{u})^T]$; $\mathbf{F}_d$ denotes the interphase interaction force, μ_f is the fluid viscosity and $\mathbf{g}$ the gravity acceleration.

The TFM equations for the fluid phase can be reformulated in forms of modified N–S equations with additional source terms accounting for their difference, as follows:

$$\frac{\partial\rho_f}{\partial t}+\nabla\cdot(\rho_f\mathbf{u})=S_c, \tag{3}$$

$$\frac{\partial(\rho_f\mathbf{u})}{\partial t}+\nabla\cdot(\rho_f\mathbf{u}\mathbf{u})=-\nabla p+\nabla\cdot\mathbf{T}+\mathbf{S}_m, \tag{4}$$

where S_c and $\mathbf{S}_m$ are the source terms in the continuity equation and the momentum equation, respectively, the pressure p will be calculated by the equation of state $p=\rho_f c_s^2$ and

$$S_c=-\frac{\rho_f}{\varepsilon}\left(\frac{\partial\varepsilon}{\partial t}+\mathbf{u}\cdot\nabla\varepsilon\right), \tag{5}$$

$$\mathbf{S}_m=S_c\cdot\mathbf{u}+\frac{1}{\varepsilon}(\mathbf{F}_d+\mathbf{T}\cdot\nabla\varepsilon)+\rho_f\mathbf{g}. \tag{6}$$

In this work, we restrict our discussion to 2D configuration, while the 3D cases can be solved with similar approach. For the 2D LBM scheme, we start our work by using D2Q9 model with external force (Qian et al., 1992), as follows:

$$f_i(\mathbf{x}+\mathbf{c}_i\delta t,t+\delta t)-f_i(\mathbf{x},t)=-\frac{1}{\tau}[f_i(\mathbf{x},t)-f_i^{(eq)}(\mathbf{x},t)]+F_i, \tag{7}$$

where $f_i(\mathbf{x},t)$ is the distribution function of direction i at local $\mathbf{x}$ and time t, τ is the dimensionless relax time and F_i denotes the external force term, which mainly includes the drag force and gravity for a particle-fluid two-phase flow. And the sound speed $c_s=(\sqrt{3}/3)$ for D2Q9 model. Here the equilibrium function is calculated exactly following the formula of Qian et al. (1992), which is $f_i^{(eq)}=\rho\omega_i[1+(\mathbf{e}_i\cdot\mathbf{u}/c_s^2)+((\mathbf{e}_i\cdot\mathbf{u})^2/2c_s^4)-(u^2/2c_s^2)]$, and $\mathbf{e}_i$ is the discrete velocity, ω_i is the weight coefficient, As Qian et al. (1992) has proved, Eq. (7) corresponds to the N–S equations. To account for the difference between the fluid equations of N–S and TFM, we modify Eq. (7) by attaching an additional term as in Cheng and Li (2008), such that

$$f_i(\mathbf{x}+\mathbf{c}_i\delta t,t+\delta t)-f_i(\mathbf{x},t)=-\frac{1}{\tau}[f_i(\mathbf{x},t)-f_i^{(eq)}(\mathbf{x},t)]$$