International Journal of Heat and Mass Transfer 93 (2016) 477–490

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Lattice Boltzmann simulation of two cold particles settling in Newtonian fluid with thermal convection

Bo Yang [a], Sheng Chen [a,b,c,*], Chuansheng Cao [a], Zhaohui Liu [a], Chuguang Zheng [a]

[a] State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan 430074, China
[b] Faculty of Engineering, The University of Nottingham, University Park, Nottingham NG7 2RD, UK
[c] Institute for Modelling and Simulation in Fluodynamics, Nanoscience and Industrial Mathematics "Gregorio Millan Barbany", Universidad Carlos III de Madrid, Getafe 28903, Spain

ARTICLE INFO

Article history:
Received 20 March 2015
Received in revised form 16 October 2015
Accepted 17 October 2015

Keywords:
Particle sedimentation
Thermal convection
Lattice Boltzmann method

ABSTRACT

The knowledge on the sedimentation of double particles is important in multiphase flow research. However, the available studies almost all are limited on the sedimentation of isothermal particles where there is no thermal convection between particles and fluid. In order to reveal the effects of thermal convection, in the present work the behavior of two cold particles freely settling in vertical channel is investigated using the lattice Boltzmann method (LBM) with direct-forcing immersed boundary method (IBM). By changing the initial separation distance and relative angle between two cold particles, the effects of these initial parameters on the interaction of cold particles settling in Newtonian fluid are also investigated. With different initial separation distance and relative angle between the two cold particles, we find that there are three regimes, namely repulsion, attraction and transition, during the sedimentation. The effects of thermal convection on the interactions between the two cold particles are revealed comprehensively for the first time by making comparisons between sedimentation of the two cold particles and their isothermal counterparts. The results reveal that thermal convection significantly influences the interactions between two cold particles during the sedimentation. The repulsive process will be enhanced due to thermal convection especially when the two cold particles approach each other very close. In addition, we observe the "drafting, kissing and tumbling" (DKT) phenomenon occurs earlier due to thermal convection. Owing to thermal convection, the attraction and repulsion process in the transition regime are enhanced. Moreover, thermal convection enhances the oscillations of trajectories of the two cold particles.

1. Introduction

Particulate flows are common in nature and industrial applications, such as sand storm and fluidized bed reactor. Particle–fluid, particle–particle and particle–wall interaction dominate the dynamic of particulate flow systems. In order to deepen our insight into such important flows, many researchers investigated these interactions by experiments and numerical simulations.

Fortes et al. [1] experimentally investigated the behavior of isothermal spherical particles falling against gravity for the first time. They found the essential mechanism dominating the interactions between spherical particles was associated with wakes. It was observed that the trailing particle was sucked into the wake of the leading one with increasing velocity. When the two particles came close to almost contact, their center-line rotated and finally the trailing particle overtook the other. This phenomenon was described by them as "drafting, kissing and tumbling" (DKT) phenomenon. The phenomenon was also observed in many other experimental studies [2,3].

Hu et al. [4] simulated the DKT phenomenon in two-dimension based on the solution of Navier–Stokes (NS) equations and equations of particles' motion. They found the mechanism leading to isothermal particles' tumbling in the DKT motion was associated with long bodies. In their paper, long bodies denoted two settling particles in the tumbling process, in which the line of centers between the two particles rotated from across to along the stream as the particles were sucked together.

Feng et al. [5] studied the behavior of two isothermal circular particles settling under gravity in a vertical channel using the finite-element method (FEM). In their simulations, particle–fluid, particle–wall and particle–particle interaction were investigated. They found the mechanisms governing the particulate flow systems were associated with lubrication, long bodies, and wakes. As the particles to fluid density, or in the other words, as the

* Corresponding author at: State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan 430074, China

E-mail address: shengchen@hust.edu.cn (S. Chen).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.10.030
0017-9310/

Reynolds number of particles (Re) increased, different regimes appeared. For the two particles with initial vertical arrangements at low Re, they experienced an approaching process due to attraction but no DKT phenomenon appeared during the sedimentation. The DKT phenomenon occurred when the Re of particles was large enough. They also found in their simulations the channel walls had a strong influence on the interactions of particles as the walls tended to push the particles together. The DKT phenomenon was also reproduced in many other simulations not only in two-dimension [6,7] but also in three-dimension [8,3,9–13].

The effects of initial separation distance and relative angle between the two isothermal particles on the interactions of particles were investigated comprehensively by the present authors for the first time [13]. Three regimes (repulsion, attraction and transition regime), relying on the initial separation distance and relative angle between the two particles, were identified. The three regimes had a general characteristic: repulsion force would be generated between the two particles when initial relative angle between the two particles was small; attraction force would be generated when initial relative angle was large; attraction and repulsion force would periodically dominate the process when initial relative angle was neither small nor large.

The studies mentioned above all are limited in isothermal situations. However, in practical applications particles' temperature is usually different from that of surrounding fluid, so heat transfer will emerge between particles and surrounding fluid and it will influence the motion of particles. Thus the investigation on the dynamics of particles freely settling with heat transfer is very important to deeply understand particles' behavior, such as particle pattern in fluidized bed reactors. Gan et al. [14] investigated the sedimentation of thermal particles in a Newtonian fluid using FEM with Arbitrary Lagrangian–Eulerian (ALE) scheme for the first time. The effects of thermal convection on the motions of settling particles were investigated. They found particles tended to repel each other when they were colder than fluid and attract each other when they were hotter. Various scenarios for different Grashof numbers (Gr) were also discussed. At higher Gr, the initial DKT motion persisted longer and steady vertical distance between particles became smaller. Recently, behavior of 30 hot particles settling under gravity in a newtonian fluid was studied in three-dimension using LBM by Zahra Hashemi et al. [15]. Hydraulic and thermal convection interactions between particles and surrounding fluid were also studied. However, the effects of initial separation distance and relative angle on interactions between thermal particles were neglected in all existing open literature.

In order to deepen our understanding on the combined effects of thermal convection, initial separation distance and relative angle of particles on particulate flows, in this paper, we numerically investigate the effects of thermal convection on the interactions of two cold particles freely settling in Newtonian fluid with different initial parameters and make a comparison with their isothermal counterparts.

2. Numerical method

Nowadays the lattice Boltzmann method (LBM) has been matured as a powerful tool to model complicated fluid flows. The LBM is particularly applicable in particulate flow systems involving heat transfer and moving boundaries [16,17].

Originally the LBM is evolved from lattice gas automata, which utilizes a discrete lattice and discrete time. The Navier–Stokes (NS) equations can be derived from lattice Boltzmann equation (LBE) [18]. In the LBM, the fluid domain is discretized to regular lattice nodes, and the fluid is regarded as pseudo fluid particles which move along on the lattice lines in discretized directions.

To solve the interaction on the moving boundaries, many boundary methods have been introduced into LBM. Recently, the immersed boundary method (IBM) was introduced to LBM. The IBM was first introduced by Peskin [19,20]. It can be divided into two categories: the feedback forcing method and direct-forcing method, based on the ways to calculate the boundary force. For the feedback forcing method [19–23], the boundary force is obtained from feedback process. However, for the direct-forcing method [24–30], the boundary force is directly derived from NS equations or LBE. Kang et al. [31] combined the direct-forcing method with diffuse or sharp interface scheme and successfully applied it to LBM.

To model the temperature field, in this work, we use the double-population thermal lattice Boltzmann equation.

2.1. Flow field

The evolution equation with IBM for fluid flow field can be expressed as

$$f_i(\mathbf{x}+\mathbf{c}_i\Delta t, t+\Delta t) - f_i(\mathbf{x}, t) = \Omega_i(f) + F_i\Delta t + R_i\Delta t \tag{1}$$

where $f_i(\mathbf{x}, t)$ is distribution function for flow field, Δt is the time step, F_i and R_i are the discrete forcing term for the immersed boundary force, the buoyancy force, respectively. $\Omega_i(f)$ is the discrete collision operator in multiple-relaxation-times (MRT) models and is formulated as [32,33]

$$\Omega_i(f) = -\sum_j (M^{-1}SM)_{ji}(f_j - f_j^{eq}) \tag{2}$$

where f_j^{eq} is the equilibrium distribution function and $S = diag(\tau_0, \tau_1, \tau_2, \ldots, \tau_{i-1})^{-1}$ is a positive diagonal matrix. We employ D2Q9 model here and $S = diag(1, 0.2, 0.1, 1, 1.2, 1, 1.2, 1/\tau_f, 1/\tau_f)$, where τ_f is the momentum relaxation time. The discrete velocity $\vec{c}_i$ is defined as

$$\mathbf{c}_i = \begin{cases} (0,0) & i=0 \\ c(\cos[(i-1)\pi/2], \sin[(i-1)\pi/2]) & i=1,2,3,4 \\ \sqrt{2}c(\cos[(2i-1)\pi/4], \sin[(2i-1)\pi/4]) & i=5,6,7,8 \end{cases} \tag{3}$$

where $c = \Delta x/\Delta t$ is the lattice speed. Δx is the lattice grid spacing. The equilibrium distribution function f_i^{eq} is defined by

$$f_i^{eq} = \omega_i\rho\left[1 + \frac{\mathbf{c}_i\cdot\mathbf{u}}{c_s^2} + \frac{(\mathbf{c}_i\cdot\mathbf{u})^2}{2c_s^4} - \frac{|\mathbf{u}|^2}{2c_s^2}\right] \tag{4}$$

where $\omega_0 = \frac{4}{9}, \omega_{1-4} = \frac{1}{9}$ and $\omega_{5-8} = \frac{1}{36}$, and $c_s = c/\sqrt{3}$ is the sound speed.

The momentum relaxation times τ_f is related to the kinematic viscosity v and given by

$$\tau_f = \frac{v}{c_s^2\Delta t} + 0.5 \tag{5}$$

The transfer matrix M is given by

$$M = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ -4 & -1 & -1 & -1 & -1 & 2 & 2 & 2 & 2 \\ 4 & -2 & -2 & -2 & -2 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & -1 & 0 & 1 & -1 & -1 & 1 \\ 0 & -2 & 0 & 2 & 0 & 1 & -1 & -1 & 1 \\ 0 & 0 & 1 & 0 & -1 & 1 & 1 & -1 & -1 \\ 0 & 0 & -2 & 0 & 2 & 1 & 1 & -1 & -1 \\ 0 & 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 \end{pmatrix} \tag{6}$$