International Journal of Heat and Mass Transfer 126 (2018) 753–764

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Thermal effects on the sedimentation behavior of elliptical particles

A. Xu, L. Shi, T.S. Zhao *

HKUST Energy Institute, Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Hong Kong, China

ARTICLE INFO

Article history:
Received 19 March 2018
Received in revised form 13 May 2018
Accepted 15 May 2018

Keywords:
Particle flow
Lattice Boltzmann method
Heat transfer
Particle sedimentation

ABSTRACT

We investigate thermal effects on the sedimentation behavior of elliptical particles via particle-resolved direct numerical simulation. Two scenarios of fluid-particle heat transfer in an infinitely long channel are considered: one is a cold particle settling in a hot fluid, while the other is a hot particle settling in a cold fluid. Results show that when an elliptical particle sediment in a wide channel (i.e., the block ratio is large), in addition to the two sedimentation modes reported in the literature for the particle sediments in isothermal fluids, there exist another three modes arising from thermal effects: the tumbling mode, the anomalous rolling mode and the inclined mode. Specifically, for a cold particle settling in a hot fluid, we found the tumbling mode and inclined mode, while for a hot particle settling in a cold fluid, we found the anomalous rolling mode and inclined mode. The phase diagrams of the sedimentation modes as functions of Archimedes and Grashof numbers are given. Analyses of the relationship between particle Reynolds number and Grashof number indicates that the mode presented depends on the competition between channel wall confinement, combined forced and natural convection.

1. Introduction

The motion of solid particles in a viscous fluid has wide applications in various engineering fields. For example, in suspension redox flow batteries, the size, shape, and composition of both active material particles and conductive material particles are intrinsically coupled parameters affecting the rheology and transport properties of suspension fluid [1]. In these scenario applications, both fluid inertia and viscosity are finite, the behavior of the fluids and solid particles are strongly coupled, thus particle motion shows rich physical phenomena. Among various parameters affecting particle motion, particle shape plays a critical role. During the past several decades, motion of spherical particles has drawn much attention due to the symmetry of particle shape. Recently, more researches focus on the motion of non-spherical particles to truly discover real-world particle transport processes.

For a two-dimensional (2D) elliptical particle or a three-dimensional (3D) ellipsoid particle sedimentation, eight distinct modes have been reported [2–5]: the horizontal mode, the horizontal II mode, the inclined mode, the inclined II mode, the vertical mode, the oscillatory mode, the anomalous rolling mode and the spiral mode. The horizontal mode refers to particle sediments horizontally with a constant velocity along the centerline of channel; while the horizontal II mode refers to particle sediments horizontally with oscillating pattern. In the inclined mode, particle sediments with a constant velocity and a constant inclination to horizontal; while in the inclined II mode, inclined particle sediments with oscillating pattern. In the vertical mode, particle sediments vertically and it can be regarded as limitation of the inclined mode with inclination angle of 90°. The oscillatory mode means particle wiggles down channel, approaching two sides of the wall periodically and oscillating around channel centerline; while the anomalous rolling mode means falling particle rotates as if it was contacting and rolling up along one of channel walls. The spiral mode is unique in 3D ellipsoid particle settling, and it indicates particle spirals around channel centerline while the angle between the particle axis and channel centerline keeps constant. The above-mentioned modes are usually resulted from two effects: one is channel geometry effects, which is characterized by blockage ratio as channel width over particle axis length; the other is particle inertial effect, which is characterized by particle Reynolds number as a function of particle size and particle density. Specifically, Xia et al. [2] reported the horizontal mode and the horizontal II mode for a 2D elliptical particle sedimentation in a wide channel as particle density varies. In addition, they identified the oscillatory mode, the anomalous rolling mode (known as the tumbling mode in their paper), the vertical mode, the inclined mode and the horizontal model as blockage ratio varies when particle sediments in a narrow channel. By carrying out 3D simulation, Swaminathan et al. [3] found oscillatory and inclined modes for an ellipsoidal particle settling in a tube. To further verify whether the tumbling

* Corresponding author.
E-mail address: metzhao@ust.hk (T.S. Zhao).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.073
0017-9310/

mode, the vertical mode and the horizontal mode found in 2D simulations will occur in 3D simulation, Huang et al. [4] investigated the sedimentation of a prolate ellipsoid in both circular and square tubes, and they confirmed the spiral mode and the vertically inclined mode. Moreover, the phase diagram of flow regimes as functions of tube blockage ratio and Reynolds number are obtained. Later, same authors extended their investigation to study the sedimentation of an oblate ellipsoid [5].

The above studies focused on isothermal suspended particles where there is no thermal convection between suspended particles and surrounding fluids. However, thermal effects are not always negligible in studying particle suspension since heat transfer might significantly alter the particle kinematics. For example, Gan et al. [6] demonstrated that thermal convection can change sedimentation behavior of a 2D circular particle via two factors: one is the competition between natural and forced convection, and the other is wall effects. Feng and Michaelides [7] investigated heat transfer in particulate flows with a group of interacting circular particles and they showed how the local temperature field and buoyancy force affects both sedimentation process and energy transfer. Deen et al. [8] investigated heat transfer of dense particulate systems in both stationary beds and fluidized beds. Hu and Guo [9] identified five competing mechanisms for lateral migration of a circular particle with thermal convection, namely the wall repulsion due to lubrication, the inertial lift related to shear slip, the lift due to particle rotation, the lift due to the curvature of the undisturbed velocity profile and the lift induced by thermal convection. However, it should be noted that in all previous studies involving particulate flows with heat transfer, only solid particles as the circular shape were considered to reduce the complexity of the problem.

With the knowledge presented in the above studies, one may ask what complex phenomena would arise for an elliptical particle sedimentation in non-isothermal fluids? To answer this question, in this work, we present a systemic investigation of thermal effects on elliptical particle sedimentation behavior. The rest of the paper is organized as follows: In Section 2, we first present the double-distribution multiple-relaxation-time lattice Boltzmann (LB) model for simulating fluid flows and heat transfer, followed by particle-resolved LB model for simulating particle suspension. In Section 3, the present LB model is evaluated by verifying sedimentation behavior of an elliptical particle in isothermal fluids, and a cold circular particle in a hot fluid. After that, numerical simulations are carried out to study a cold elliptical particle settling in a hot fluid and a hot elliptical particle settling in a cold fluid with various Archimedes and Grashof numbers.

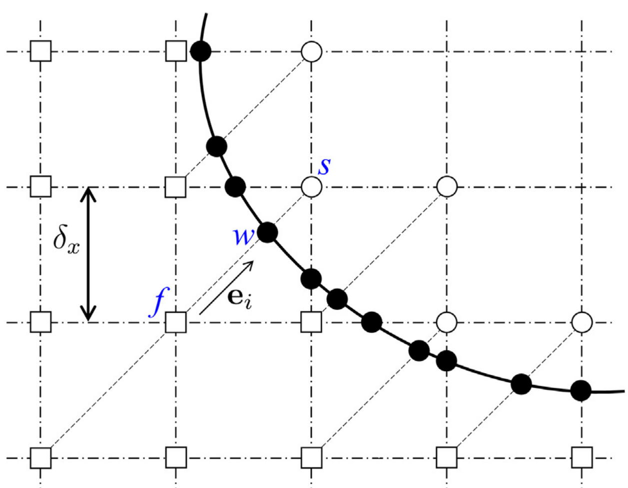


Fig. 1. Schematic drawing of curve wall boundary condition.

2. Numerical method

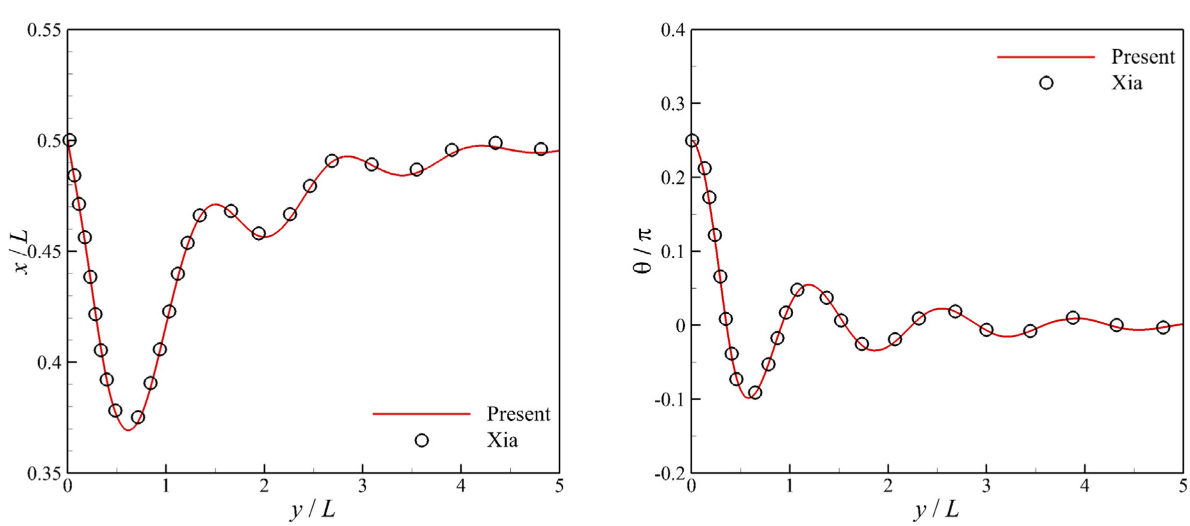
2.1. The double-distribution-function LB model for fluid flow and heat transfer

Incompressible fluid flows can be described by the Navier-Stokes equations; while buoyancy effect caused by temperature variation can be approximated by the Boussinesq approximation [10–13]. Then, the governing equations of fluid flow and heat transfer can be written as

$$\nabla \cdot \mathbf{u} = 0 \tag{1a}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho_0}\nabla p + \nu \nabla^2 \mathbf{u} + g\beta_T (T - T_0)\hat{\mathbf{y}} \tag{1b}$$

$$\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T = \kappa \nabla^2 T \tag{1c}$$



(a) Trajectories (b) Orientations

Fig. 2. Time histories of the elliptical particle settling in a wide channel ($\beta = 4$).