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Effect of Thermal Convection and Mass Transfer on Particle Motion during Sedimentation: A Numerical Study

Junjie Hu[1,2,*] and Dongke Sun[1]

[1] *School of Mechanical Engineering, Southeast University, Nanjing, Jiangsu 211189, China*
[2] *Hubei Key Laboratory of Engineering Modeling and Scientific Computing, Huazhong University of Science and Technology, Wuhan, Hubei 430074, China*

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Abstract. The sedimentation of a particle cluster with heat and mass transfer is studied with the lattice Boltzmann method. To investigate the effect of thermal convection and mass transfer on the motion of the particle cluster, four cases are studied, namely, without heat and mass transfer, with heat transfer, with mass transfer and with heat and mass transfer. Compared to mass transfer, the effect of thermal convection is more dominant, which affects the motion of the particle cluster significantly. The particle-particle interaction is enforced by thermal convection, and the oscillation of the average settling velocity of the particle cluster is more intense. Besides, with mass transfer between the particles and the fluid, the mass of the particles decreases, the motion of the particles is more sensitive to the fluid flow, the velocity fluctuation of the particle cluster is more intense, the distribution of the particle cluster is more inhomogeneous.

AMS subject classifications: 35Q30, 76D05

Key words: Particle sedimentation, thermal convection, mass transfer, lattice Boltzmann method.

1 Introduction

The motion of inertial particles in the fluid is ubiquitous, which plays a key role in industrial and natural sciences, and thus the sediment dynamics is studied by numerous researchers [1–4]. For example, Feng et al. [1] studied the sedimentation of numerous circular particles, and reported the Rayleigh-Taylor instability during the sedimentation. Zaidi et al. [2] investigated the average settling velocity of the particle cluster, and pointed out that the inhomogeneous particle distribution affected the average settling velocity of

*Corresponding author.
Email: hujunjie@cug.edu.cn (J. Hu)

the particle cluster significantly. Zhang et al. [3] studied the sedimentation of a particle pair in a shear-thinning power-law fluid with the multiple-relaxation-time lattice Boltzmann method, and reported that the particle pair experienced several different movement states depending on the initial geometrical configuration. To deepen the understanding of the entrainment mechanism, Li et al. [4] conducted a two-dimensional numerical investigation of the particle entrainment in the presence of a large downstream circular obstacle. However, under some cases, like coal combustion and food processing, the particle and the fluid are non-isothermal, meanwhile, the particle is composed of different components, some insoluble while some soluble in the fluid, besides the hydrodynamic force, the particle motion is affected by thermal convection and mass transfer.

Some researchers investigated the effect of thermal convection on the particle motion [5–14]. For example, Gan et al. [5] studied a cold particle settling in a vertical channel with the finite element method, and reported that the settling behavior of the particle is significantly different from the isothermal case. Gan et al. pointed out that the settling behavior of the non-isothermal particle was the competitive result between forced convection and thermal convection. Mandujano et al. [7] studied thermal levitation, namely, a particle with a density slightly different from the fluid kept still at the steady state due to thermal convection, and discussed the stability of thermal levitation. Wang et al. [9] studied convective heat transfer between gas and a particle cluster in a circulating fluidized bed riser, and pointed out that the heat flux of the individual particle inside the cluster was smaller than that of an isolated particle. At the same time, they reported that the convective heat transfer coefficient increased with the increase of the porosity of the particle cluster, because more gas passed through the particle cluster.

Though some researchers studied mass transfer between the particle and the fluid, the focus is limited to the rate of mass transfer [15–19], while the effect of mass transfer on the particle motion is investigated rarely. For example, Wang et al. [18] studied mass transfer between air and a particle cluster in a circulating fluidized bed, and pointed out that the rate of mass transfer was reduced due to the particle clustering, since less air passed through the particle cluster. In the study, the particle cluster is fixed and the uniform air flow is imposed at the inlet, thus, the particle motion and mass transfer is decoupled artificially. However, the reality is that the particle properties, such as density, mass and moment inertia, will vary with mass transfer between the particle and the fluid, which affects the particle motion significantly.

During the sedimentation of the particles with heat and mass transfer, like coal combustion and food processing, the temperature and concentration distribution is related to the fluid flow, which affects the particle motion, conversely, the particle motion affects the fluid flow, temperature and concentration distribution. Thus, the sedimentation of the particle cluster with heat and mass transfer is complex, where the fluid flow, particle motion, thermal convection and mass transfer affect each other.

The rest of the paper is organized as follows. Section 2 describes the problem, Section 3 introduces the numerical method, and Section 4 validates our code. Section 5 are the results and discussions, where the effect of thermal convection and mass transfer on the