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Numerical Investigation of "Frog-Leap" Mechanisms of Three Particles Aligned Moving in an Inclined Channel Flow

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Abstract. Intrigued by our recent experimental work (H. Yamaguchi and X. D. Niu, J. Fluids Eng., 133 (2011), 041302), the present study numerically investigate the flow-structure interactions (FSI) of three rigid circular particles aligned moving in an inclined channel flow at intermediate Reynolds numbers by using a momentum-exchanged immersed boundary-lattice Boltzmann method. A "frog-leap" phenomenon observed in the experiment is successfully captured by the present simulation and flow characteristics and underlying FSI mechanisms of it are explored by examining the effects of the channel inclined angles and Reynolds numbers. It is found that the asymmetric difference of the vorticity distributions on the particle surface is the main cause of the "frog-leap" when particle moves in the boundary layer near the lower channel boundary.

AMS subject classifications: 70B99,76M28

Key words: Frog-leap, fluid-structure interactions, inclined channel flow, lattice Boltzmann method, immersed boundary method.

1 Introduction

The fluid-structure interactions (FSI) occur in many applications in industry and science. Especially, in many applications of fuid mechanics, geology, biology and chemistry, there are systems consisting of particle transportation in the fluid or gas [1], such processes of rivers carrying sand, flow in hydraulic and pneumatic pipes with sedimentation of impurities and flow of blood in capillary vessels.

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The movement of particles in the fluids, assuming their high density or high volume, changes significantly the character of the flow. The underlying multi-physical mechanisms of these FSI problems are far from understanding and have attracted many research interests from fluid scientists in past decades [2–20]. There have been extensive theoretical, numerical and experimental studies of hydrodynamic interactions of large collections of particles at low Reynolds numbers [2–7]. Recent work has shown that a spherical cloud of particles settling in a viscous fluid spreads and eventually evolves into a toroidal shape and separates into a cascade of smaller clumps [6]. Particle interactions and clustering at intermediate Reynolds numbers are complicated by the fluid inertia and have been studied by Jenny et al. [8], Ardekani and Rangel [9] and Daniel et al. [10]. Other dynamics of large collections of particles include, but are not limited to, sedimentation [11–13], particle assembly [14], magneto-hydrodynamic flows [15], biofluid and bio-mechanics (such as micro-organism colony growth through clustering mechanisms and in diffusive mixing, etc) [16–20].

Much of the earlier and recent works on the FSI flows focused on collective behavior or dynamics of large collections of particles. In contrast, there have been relatively few studies on pair interactions between neighboring particles and turning couples where the rich dynamics of the particles and their surrounding fluids are exist and effects of fluid damping, fluid inertia are important [21–23].

In present work, we carry out a numerical investigation of three particles aligned moving up in the carried fluid in an inclined channel in the intermediate-Reynolds-number range. This study is intrigued by our recent experimental study of solid-liquid two-phase flow measurement using an electromagnetically induced signal measurement method [24], in which we often observed a ″frog-leap″ phenomenon of a lagged particle jumping over the particles ahead when particles perform an aligned move-up in an inclined channel flow. The goal of this paper is twofold. First, we introduce an efficient lattice Boltzmann method (LBM) for solving the two-dimensional particulate flows with a momentum-exchanged immersed boundary technique [25]. The method for coupling the fluid and solid dynamics is inherently based on collision kinetics of particles [26] and does not introduce additional constraints on the integration time step, hence allowing an efficient simulation of multiple, arbitrarily moving particles in the fluids. The second goal is to discover the rich fluid dynamics of the ″frog-leap″ phenomenon of three particles aligned moving up in the inclined channel flows at intermediate Reynolds numbers.

The rest of the present paper is organized as follows. Section 2 gives a general description of the LBM with the momentum-exchanged immersed boundary technique. The force calculations related to particle-particle, particle-wall and inertia are also introduced. In order to validate the present method, in Section 3, two cases, a circular cylinder oscillating horizontally in a fluid and two circular particles settling in a vertical channel, are tested. In Section 4, the fluid dynamics and underlying FSI mechanisms of the ″frog-leap″ phenomenon of three particles aligned moving up in an inclined channel flow are explored. The effects of the channel inclined angle and flow Reynolds numbers are discussed, respectively. Finally a conclusion is given in Section 5.