

Direct Numerical Simulation of Multiple Particles Sedimentation at an Intermediate Reynolds Number

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Abstract. In this work the previously developed Lattice Boltzmann-Direct Forcing/Fictitious Domain (LB-DF/FD) method is adopted to simulate the sedimentation of eight circular particles under gravity at an intermediate Reynolds number of about 248. The particle clustering and the resulting Drafting-Kissing-Tumbling (DKT) motion which takes place for the first time are explored. The effects of initial particle-particle gap on the DKT motion are found significant. In addition, the trajectories of particles are presented under different initial particle-particle gaps, which display totally three kinds of falling patterns provided that no DKT motion takes place, i.e. the concave-down shape, the shape of letter "M" and "in-line" shape. Furthermore, the lateral and vertical hydrodynamic forces on the particles are investigated. It has been found that the value of Strouhal number for all particles is the same which is about 0.157 when initial particle-particle gap is relatively large. The wall effects on falling patterns and particle expansions are examined in the final.

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1 Introduction

Solid particles immersed in a viscous fluid lead to a two-phase flow problem, which is very common in nature and many industrial processes, including atmospheric currents,

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aerosol deposition, pharmaceutical sciences, hydraulic fracturing, fluidized beds and so on. It is important to understand particle-particle interactions and particle-fluid interactions, and their microstructure evolution in fluids, which usually relates to the collective behaviour and self-organization of solid particles, and is central to physical phenomena such as cloud formation, particle suspension and particle sedimentation. In comparison with experimental measurements, numerical simulations have remarkable advantages in exploring the inter-phase interactions in multiphase flows, especially for direct numerical simulation (DNS) methods. In a DNS method, the fluid flow and particle motion are coupled to study the dynamics of individual particles suspended in fluids, which is the highest-resolution numerical method without any empirical model.

So far extensive theoretical and numerical models (Hocking, 1964; Crowley, 1971; Leichtberg et al., 1976; Brady and Bossis, 1988; Mo and Sangani, 1994; Feng and Joseph, 1995; Alexander et al., 2003; Nguyen and Ladd, 2005; Metzger et al., 2007; Koch and Subramanian, 2011) have been proposed to simulate the dynamics of many interacting particles in a viscous fluid at quasi-steady zero-Reynolds-number or low Reynolds number by ignoring the transient and nonlinear inertia effects, which are becoming crucial at intermediate Reynolds numbers or high Reynolds numbers. The hydrodynamic interactions between particles mediated by the fluid and particle interactions with the wall are highly nonlinear and the dynamics of multiple particles can be quite complex by taking into account the fluid inertia, which also introduces unsteadiness to particulate flow problems. In comparison with the numerical studies at low Reynolds numbers, much fewer studies have been found on particle interactions and clustering at intermediate Reynolds numbers due to the difficulty in dealing with the boundaries between particles and fluid in a DNS framework. Jenny et al. (2004) numerically investigated a sphere falling or ascending under the action of gravity in a Newtonian fluid at intermediate Reynolds numbers. Their results show that the sphere undergoes a transition to a full spatio-temporal chaos in the range of asymptotic average Reynolds number lying between 205 and 310, and the scenario is significantly different for falling and for ascending spheres (Jenny et al., 2004). Recently, Yacoubi et al. (2012) presented remarkable work by studying the two-dimensional dynamics of horizontal arrays of settling cylinders in a container at intermediate Reynolds numbers of 200 based on the immersed interface method. They found that in the case of odd-numbered arrays, the middle cylinder is always leading, whereas in the case of even-numbered arrays, the steady-state shape is concave-down. Furthermore, in large arrays (the number of particles greater than 5) the outer pairs tend to cluster. However, they did not further investigate the influence of initial particle-particle gaps on falling patterns, especially for small or large initial gaps, which is expected to be central to particle clustering and also to the resulting well-known 'Drafting-Kissing-Tumbling (DKT)' motion. Furthermore, it is helpful to better understand the dynamics of interacting particles moving freely under the action of gravity, buoyancy and hydrodynamic forces by studying the lateral and longitudinal expansions of the array. In addition, it is also necessary to examine the wall effects, i.e. the effects of the width of container on the dynamics of particle clustering. The present work is mostly