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Evaluation of Three Lattice Boltzmann Models for Particulate Flows

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Abstract. A comparative study is conducted to evaluate three types of lattice Boltzmann equation (LBE) models for fluid flows with finite-sized particles, including the lattice Bhatnagar-Gross-Krook (BGK) model, the model proposed by Ladd [Ladd AJC, *J. Fluid Mech.*, 271, 285-310 (1994); Ladd AJC, *J. Fluid Mech.*, 271, 311-339 (1994)], and the multiple-relaxation-time (MRT) model. The sedimentation of a circular particle in a two-dimensional infinite channel under gravity is used as the first test problem. The numerical results of the three LBE schemes are compared with the theoretical results and existing data. It is found that all of the three LBE schemes yield reasonable results in general, although the BGK scheme and Ladd's scheme give some deviations in some cases. Our results also show that the MRT scheme can achieve a better numerical stability than the other two schemes. Regarding the computational efficiency, it is found that the BGK scheme is the most superior one, while the other two schemes are nearly identical. We also observe that the MRT scheme can unequivocally reduce the viscosity dependence of the wall correction factor in the simulations, which reveals the superior robustness of the MRT scheme. The superiority of the MRT scheme over the other two schemes is also confirmed by the simulation of the sedimentation of an elliptical particle.

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Key words: Lattice Boltzmann equation, finite-sized particles, numerical performance, sedimentation in channel.

1 Introduction

Particulate flows occur widely in both industrial and scientific applications, such as river sediment resuspension and transport, blood clogging and cell transport in arteries and

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veins, DNA and polymer molecules [1, 2], colloidal suspensions, etc. Owing to the importance of these applications, experimental and numerical studies have been attracting considerable attention in the past decades.

In particulate flows, the fluid phase can be well-described by the Navier-Stokes (NS) equations, while the description of the particle phase can be classified into two categories, i.e., the point-particle method and the finite-size particle method. In the point-particle method, a solid particle is considered as a mass point with negligible size and shape, and its position and velocity are traced in a Lagrangian manner. The interactions between fluid and particles are modeled by some empirical or semi-empirical relations. The point-particle method is suitable for most engineering applications with a large number of particles with sizes far smaller than the flow length scale. However, the point-particle method is not enough to reveal the fundamental mechanism of the fluid-particle interactions. In contrast, the size and shape of a particle are considered in the finite-size particle method, and the particle-fluid interactions can be described through the no-slip boundary conditions on the particle interface directly. Therefore, this method can be viewed as a direct numerical simulation method for particulate flows. Several direct numerical simulation methods, including the finite element method (FEM) and the finite volume method (FVM), have been developed within this framework [3–6]. However, these methods usually suffer from expensive computational costs due to frequent remeshing and projection in simulations of particulate flows.

Besides these conventional methods that solve the NS equations, the lattice Boltzmann equation (LBE), which is a method based on kinetic theory, has also been applied to particulate flows [7–16]. The first application of LBE to particulate flows with finite-sized particles is attributed to Ladd [10, 11]. In this method [10, 11], a fixed regular grid system is used to represent the flow field and the solid particle. A modified bounce-back rule [11] is proposed to treat the no-slip boundary condition on the particle-fluid interface, and an approach based on momentum exchange is developed to calculate the hydrodynamic force exerting on the solid particle. It is assumed that the fluid can pass through the boundary of the suspended solid particle and occupy its interior domains. In this way, both the interior and exterior fluid nodes can be treated in an identical manner as the particle moves on the lattice. It is noted that in Ladd's model the particle behaves like a rigid one with the combined mass and moment of inertia of the shell plus the internal fluid. Consequently, when the density ratio of particle to fluid is close to or smaller than unity, numerical instability will occur in the particle update procedure [16–18]. To overcome this limit, a number of methods have been developed to partially or fully remove the internal fluid of particle [12, 13, 19].

Another problem of Ladd's model is that the particle surface is represented by the boundary nodes which are actually a set of points located at the middle of the link between a fluid node and a solid node. This arrangement means that the body surface is approximated by a stair-step shape. As the particle moves, this will generate some noisy forces and further bring fluctuations to the particle velocities. Some improvements [20–23] have been proposed for more accurate representation of the particle shape