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Particulate Flow Simulation via a Boundary Condition-Enforced Immersed Boundary-Lattice Boltzmann Scheme

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Abstract. A boundary condition-enforced immersed boundary-lattice Boltzmann method (IB-LBM) for the simulation of particulate flows is presented in this paper. In general, the immersed boundary method (IBM) utilizes a discrete set of force density to represent the effect of boundary. In the conventional IB-LBM, such force density is pre-determined, which cannot guarantee exact satisfaction of non-slip boundary condition. In this study, the force density is transferred to the unknown velocity correction which is determined by enforcing the non-slip boundary condition. For the particulate flows, accurate calculation of hydrodynamic force exerted on the boundary of particles is of great importance as it controls the motion of particles. The capability of present method for particulate flows is depicted by simulating migration of one particle in a simple shear flow and sedimentation of one particle in a box and two particles in a channel. The expected phenomena and numerical results are achieved. In addition, particle suspension in a 2D symmetric stenotic artery is also simulated.

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Key words: Lattice Boltzmann method, immersed boundary method, non-slip boundary condition, particulate flow, two-dimensional.

1 Introduction

Particulate flows have wide applications in engineering such as in river sediment re-suspension and transport, cell transport in arteries and veins, fluidized bed reactors. The numerical methods for particulate flows can be broadly classified into two categories: moving mesh method and fixed mesh method. In the moving mesh method, the body-fitted mesh is updated with particle motion. The boundary condition is imposed on the

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particle. The greatly used moving mesh method is perhaps the arbitrary Lagrangian-Eulerian (ALE) scheme [1–3]. Using this method, various flows with different particle shapes in Newtonian and non-Newtonian fluids have been successfully investigated. On the other hand, ALE approach would consume large computational effort due to expensive regeneration of geometrically adapted mesh. In contrast, the computational mesh remains unchanged in the fixed mesh method. No re-meshing procedure in accordance to the particle motion is required.

One popular approach in the fixed mesh category is the class of distributed Lagrange multiplier/fictitious domain (DLM/FD) method which was proposed by Glowinski et al [4, 5]. The basic idea of DLM/FD method is to view the particle region as a fictitious domain. A distributed Lagrange multiplier is imposed to enforce the constraints of rigid-body motion to the fictitious fluid inside the particle. Using this method, the fluid flow containing many rigid particles was successfully simulated by Glowinski et al [4,5]. Recently, the DLM/FD method has also been extended to simulate particulate flows in non-Newtonian fluids [6, 7]. Usually, the generalized Galerkin finite element scheme is incorporated into DLM/FD method.

The immersed boundary method (IBM) may be the simplest approach in the fixed mesh category. It was first introduced by Peskin [8] to model the blood flow in the human heart. This method uses a fixed Cartesian mesh to represent fluid phase, which is composed of Eulerian points. For the boundary immersed in the fluid, a set of Lagrangian points are used to represent it. The basic idea of IBM is to treat the physical boundary as deformable with high stiffness. A small distortion of the boundary will yield the force which tends to restore the boundary into its original shape. Hence, the effect of immersed boundary is depicted by the restoring force. The balance of restoring force is distributed into the Eulerian points through discrete delta function. The Navier-Stokes (N-S) equations with a body force are solved over the whole fluid-boundary domain. This approach can be efficiently applied to simulate flows with complex geometry. Recently, Fogelson and Peskin [9] indicated that IBM could also be applied to simulate flows involving suspended particles. Since then, many variants of IBM for particulate flow simulation have been presented. Based on the idea in [9], Hfler and Schwarzer [10] proposed a finite-difference method for particle-laden flows by adding a constraint force into the N-S equations to enforce rigid particle motion. The constraint force is determined by the penalty method. Using the direct forcing scheme, which was introduced by Fadlun et al. [11], Uhlmann [12] presented an improved immersed boundary method, which greatly suppresses the force oscillations, to simulate flow around suspended rigid particles. An enhanced version of direct forcing scheme was proposed by Luo et al. [13] recently to simulate spherical particle sedimentation. A nonlinear weighted technique and boundary point classification strategy at the immersed boundary are introduced to modify the velocity near the body. Li and Lai [14] applied the immersed interface method (IIM), which introduces the jump conditions for the velocity and pressure across the interface, to simulate the fixed and moving interface problems. Compared to IBM with the first-order accurate delta function, the second-order accuracy can be obtained in IIM.