Commun. Comput. Phys.
doi: 10.4208/cicp.2009.08.155

Vol. 7, No. 3, pp. 544-563
March 2010

A LB-DF/FD Method for Particle Suspensions

Deming Nie[1,2] and Jianzhong Lin[1,2,*]

[1] *State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, Hangzhou 310027, China.*
[2] *College of Metrology and Technology Engineering, China Jiliang University, Hangzhou 310018, China.*

Received 30 September 2008; Accepted (in revised version) 10 July 2009

Communicated by Sauro Succi

Available online 23 September 2009

Abstract. In this paper, we propose a lattice Boltzmann (LB) method coupled with a direct-forcing fictitious domain (DF/FD) method for the simulation of particle suspensions. This method combines the good features of the LB and the DF/FD methods by using two unrelated meshes, namely, an Eulerian mesh for the flow domain and a Lagrangian mesh for the solid domain, which avoids the re-meshing procedure and does not need to calculate the hydrodynamic forces at each time step. The non-slip boundary condition is enforced by introducing a forcing term into the lattice Boltzmann equation, which preserves all remarkable advantages of the LBM in simulating fluid flows. The present LB-DF/FD method has been validated by comparing its results with analytical results and previous numerical results for a single circular particle and two circular particles settling under gravity. The interaction between particle and wall, the process of drafting-kissing-tumbling (DKT) of two settling particles will be demonstrated. As a manifestation of the efficiency of the present method, the settling of a large number (128) of circular particles is simulated in an enclosure.

AMS subject classifications: 76T20, 76-02, 76M28

Key words: Lattice Boltzmann method, direct-forcing fictitious domain method, particle suspension, numerical simulation.

1 Introduction

Many industrial processes involve transport of solid particles suspended in a fluid medium in the form of slurries, colloids, polymers, or ceramics, such as fluidized beds in chemical reactors, water treatment, paper formation, etc. It is therefore important to understand the macroscopic transport behavior of particle suspensions, which has attracted considerable attention in the past decades, both experimentally and numerically.

*Corresponding author. *Email addresses:* nieinhz@cjlu.edu.cn (D. Nie), linjz@cjlu.edu.cn (J. Lin)

Conventional numerical methods, such as the finite volume method (FVM) and finite element methods (FEM) are not very efficient in simulating particle suspensions. One of the main obstacles is the need of generating new, geometrically adapted grids, which is a very time-consuming task especially in three-dimensional flows. Another method for suspensions, Stokesian dynamics is proposed by Brady and Bossis [1], which is limited to suspensions with simple geometries such as spheres or spheroids in creeping flow.

More recently, the lattice-Boltzmann method (LBM) has been advocated as an effective computational tool for the simulation of complex flows [2, 3]. Application of lattice Boltzmann (LB) method to simulate particles suspended in a viscous fluid was first proposed by Ladd [4, 5]. However, Ladd's model requires fluid to cross the boundary of the suspended solid particle and occupy the entire domain such that the computational nodes inside and outside the solid particle are treated in an identical manner. Thus, this method is limited to the solid particles with density larger than the fluid density. Built on Ladd's framework, Aidun [6] proposed a new approach to overcome this drawback, which works well for analysis of suspended solid particles with any solid-to-fluid density ratio. Thereafter many relevant works [7–12] have been done to demonstrate that LBM is a robust and efficient method for simulating particulate flows containing a small or a large number of particles with spherical or complex geometry. However, in both Ladd's model and Aidun's model, the non-slip condition on the particle-fluid interface is treated by the bounce-back rule and the particle surface is represented by the boundary nodes, which are essentially a set of mid-points of the links between two fixed grids. If the first-order accurate Eulerian scheme is applied, this causes fluctuations on the computation of forces on the particle and further leads to fluctuations on the velocities of the particle. Despite of this drawback the LBM has still attracted many attentions [13–16] because of its several remarkable advantages, such as easy coding, no requirement of re-meshing procedure, and computational efficiency.

The direct-forcing fictitious domain (DF/FD) method, presented by Yu [17], is based on the distributed-Lagrange-multiplier/fictitious-domain (DLM/FD) method proposed by Glowinski et al. [18] and direct-forcing immersed boundary (DF/IB) method proposed by Fadlun et al. [19]. The key idea of the DLM/FD method is that the interior domains of the particles are filled with the same fluids as the surroundings and the Lagrange multiplier (physically a pseudo body force) is introduced to enforce the interior (fictitious) fluids to satisfy the constraint of rigid body motion. However, the calculation of the particle velocity and body-force is a little more involved. Consequently, the DF/FD method is more expensive than the DF/IB method [17] in which the non-slip condition is enforced by applying an equivalent forcing term into the Navier-Stokes equations. Thus, in DF/FD method, the body-force is treated in essentially the same way as the DF/IB method. As in the DLM/FD method, DF/FD method makes use of Eulerian lattice nodes for the fluid flow field and Lagrangian nodes to represent particles, and the body-force is distributed over the particle inner domain for the constraint that all inner fluids move as a rigid-body, which allows to update particle velocities explicitly without the need of computing the hydrodynamic force and torque on the particles [17], while in the DF/IB