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Simulation of Finite-Size Particles in Turbulent Flows Using the Lattice Boltzmann Method

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Abstract. Particle laden turbulent flows occur in a variety of industrial applications. While the numerical simulation of such flows has seen significant advances in recent years, it still remains a challenging problem. Many studies investigated the rheology of dense suspensions in laminar flows as well as the dynamics of point-particles in turbulence. Here we will present results on the development of numerical algorithms, based on the lattice Boltzmann method, suitable for the study of suspensions of finite-size particles under turbulent flow conditions. The turbulent flow is modeled by the lattice Boltzmann method, and the interaction between particles and carrier fluid is modeled using the bounce-back rule. Direct contact and lubrication force models for particle-particle interactions and particle-wall interaction are taken into account to allow for a full four-way coupled interaction. The accuracy and robustness of the method is discussed by validating the velocity profile in turbulent pipe flow, the sedimentation velocity of spheres in duct flow and the resistance functions of approaching particles. Preliminary results from the turbulent pipe flow simulations with particles show that the angular and axial velocities of the particles are scattered around values of mean axial velocity and shear rate obtained from the Eulerian velocity field.

AMS subject classifications: 76F10, 76F25, 76F65, 74F10

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1 Introduction

Turbulent suspension flows are relevant in many engineering applications and natural processes. Some prominent examples involving turbulent suspension flows include aerosol and pollutant transport, dust storms, sediment transport in river basins, flow of mirco-algae in photo-bioreactors, avalanches, slurries, and several other industrial processes. In many of these examples, particles in turbulence are non-living objects, eg. sand particles in dust storms. However, there are examples like the flow in tubular photo-bioreactors or the transport of plankton in lakes, estuaries and in the ocean where the particles are actually living cells. In the latter cases, apart from studying the dynamics of particles, it is also important to study the effect of hydrodynamic stresses on the cells which might have detrimental effects and can even destroy cells. For example in photo-bioreactors, cell damage due to shear is one of the key problems in upscaling photo-bioreactors for micro-algae culture. All devices include walls and thus particle-fluid coupling in the near wall region is also more crucial for the understanding of flow physics as well as cell transport and damage.

Pioneering theoretical work to understand the rheology of dilute suspension flows was done by Einstein [1], Batchelor [2], and Batchelor et al. [3]. However, the rheology of suspensions or turbulent flows laden with particles still remain a subject of investigation as the constitutive equations relating stress to rate of strain are not generally known for such complex flows. Over the past decades, advanced computational and experimental methods have been developed and utilized to study the particle laden turbulent flows. However, most studies have either investigated the rheology of dense suspensions in laminar flows [4–7] or the dynamics of point-particles in turbulence [8–14]. The validity of the point-particle approach is questionable when particle mass loading is significant or there exists a strong coupling between the particles and the fluid phase. The finiteness of the particle size and Reynolds number becomes important for larger particles and explicit models would require solving the full non-linear Navier-Stokes equation with the proper boundary conditions at the particle surface. The simulation of these finite-size particles exhibit additional complexities due to the multi-scale nature of the problem and local flow around the particle at finite Reynolds number. Consequently, adequate description of dynamics of the finite-size particles and their coupling with the surrounding fluid has emerged as one of the major open question for the fluid dynamics community.

A significant amount of effort has been invested in the development of efficient numerical schemes for the direct numerical simulation of suspensions of solid spheres in flows at varying Reynolds number. A variety of different schemes are being developed based on finite difference or finite volume solution methods for the Navier-Stokes equations combined with efficient schemes for the implementation of the solid particle boundary conditions. Pan et al. [15] were among the first to simulate finite-size particles in turbulent channel flow to study the effect of particle size relative to the dissipative length scale on turbulence intensities and Reynolds stress. A DNS study of dilute particle laden turbulent flow in a vertical channel with large number of fully resolved finite-size rigid