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Three-dimensional particle-resolved direct numerical simulation study of behaviors of a particle settling near a vertical wall

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A B S T R A C T

Three-dimensional particle-resolved direct numerical simulation based on the multi-direct forcing and Immersed Boundary method is applied to investigate the indirect particle–wall interactions on the behaviors of a particle settling near a vertical wall in a viscous Newtonian fluid. The particle settling in unbounded domain is also simulated for the references of comparison. It is found that the sideways drift and the anomalous rotation are affected by the initial lateral position of the particle relative to the wall. The oscillation of the sedimentation velocity, rotation shifting and the three-dimensional zigzag migration are closely associated with the vortex shedding, depending on the particle terminal Reynolds number. A particle with small solid/fluid density ratio moves in a narrower range compared to a dense particle with the same Reynolds number when it is being drifted away from the wall, but if it is free of wall effect the light particle is to be more influenced by the eventual unsteadiness of its wake. It's interesting to find that the particle–fluid interaction force is also linked closely with the anomalous rotation rate. It can be proved that the particle–fluid interactions are stronger in three-dimensional cases than two-dimensional versions. First, the particle motion in the direction free of limitations is confined in a limited range due to the wall effect. Second, the rotation behavior is stronger in three-dimensional simulations. Third, the particle settling near a wall with large enough Reynolds number reaches an equilibrium stand-away distance away from the wall in three-dimensional simulations.

1. Introduction

Particulate flows are frequently encountered in nature as well as in a variety of industrial devices, such as aerosol deposition, fluvial slit sediment, powder transport, cyclone separators, fluidized beds and so on. In particulate flows, the problem of evaluating the mutual interactions between fluid and particles is a long standing issue, which has attracted the attention of many researchers [1–11]. Compared to experimental measurements, numerical simulations have a noticeable advantage in studying this problem. That is that different influence factors or flow conditions can be separately and easily studied by computer commands. However, the simulating results should be credible and reliable.

In recent twenty years, the most fundamental level of particulate flow modeling, namely the particle-resolved direct numerical simulation (PR-DNS), has advanced considerably due to the developments of numerical techniques and computer hardware. Some typical and widely applied methods of PR-DNS include the Arbitrary Lagrangian–Eulerian technique [12,13], the Distributed Lagrangian Multiplier/Fictitious Domain method [14–16], the Lattice Boltzmann method [17,18], the Immersed Boundary method [19–21] and the combined Immersed Boundary–Lattice Boltzmann method [22,23]. In PR-DNS, particle is considered as real finite volume; the hydrodynamic force acting on particle is accurately calculated by integrating the viscosity and pressure forces imposed by surrounding fluid, instead of using drag models, lift models and other such models. Therefore, PR-DNS has enough accuracy and resolution for studying the interphase interactions in particulate flows.

An active area of particulate flow basic research is the problem of a spherical particle settling near a plane wall, as it allows for the investigation of the disturbance on the symmetry of the flow field surrounding the sphere as well as the indirect interactions between particle and wall. Goldman et al. [5] theoretically analyzed the motion of a sphere "rolling" down an inclined wall under the influence of gravity in a quiescent viscous fluid, and found that the sphere cannot be in physical contact with the wall and it "slips" as if it rolls up the wall. Joseph et al. [6] simulated the interaction of a cylindrical particle and a vertical wall for a Newtonian fluid in a two-dimensional channel, and reported that the particle drifts away from the wall and the sense of rotation is anomalous when particle is close to the wall. They also found that the sideways drift velocity and the rotation rate of the particle decrease with the increasing distance from the wall. Hu et al. [7] calculated the transient motion of a cylinder sedimenting in a channel, and observed that when cylinder starts at a position close to the wall it drifts to the center of the channel and reaches a periodic oscillating orbit much faster than settling at the center. An experimental study of Liu et al.'s [8] led up to the fact that

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spheres settling near a vertical wall in Newtonian liquid are forced into anomalous rotation and drifted away from the wall to an equilibrium stand-away distance. The same conclusion was drawn by Singh and Joseph [9] through PR-DNS. Tatum et al. [10] measured the flow field surrounding a sphere sedimenting at a distance from the wall through the use of stereoscopic 3-D PIV, and found that the structure of the flow field and the motion perpendicular to the wall are dependent on the distance from the wall at which the sphere sediments. Recently, to further investigate the indirect particle–wall interactions, Luo et al. [11] conducted two-dimensional simulations on the rotation behaviors of a particle setting near a vertical wall, and concluded that the anomalous rotation is related to the wall effect and the alternate rotation shift as well as the zigzag migration is closely associated with the vortex shedding.

As we can see there is considerable literature on the problem of a particle settling near a vertical wall in viscous liquid. Experiments are totally three-dimensional while most simulations are limited to two-dimensional. The two-dimensional version of the indirect sphere–wall interactions is the motion of a circular cylinder moving perpendicular to its axis and along a single plane wall, which is more or less different from a true three-dimensional case where an axisymmetric cylinder is replaced with a centrosymmetric sphere. Joseph et al. [6] proved that the attraction between a sedimenting particle and the wall is a three-dimensional effect, i.e. exists for a sphere but not for a cylinder. Luo et al. [11] pointed out that the particle–fluid interactions are stronger in three-dimensional cases after they compared the three-dimensional simulating behaviors with two-dimensional results. Although the three-dimensional simulations have more practical meaning, true three-dimensional simulations of a particle settling near a wall have been rarely studied. In addition, when a particle is drifted away from the wall, wall effect to the particle is gradually diminished as a consequence of an increasing distance between particle and wall; particle's behaviors are supposed to make the transition from settling near a wall to settling in an unbounded domain. The similarities and distinctions of these two kinds of behaviors have been studied but less than complete. Therefore, for all of the above reasons, the behaviors of a particle settling in unbounded domain and settling near a vertical wall under different conditions are thoroughly studied by means of three-dimensional PR-DNS based on the multi-direct forcing and Immersed Boundary method [20,21]. The remainder of this paper is organized as follows. Section 2 briefly introduces the numerical methods applied in present work. Section 3 gives the validation of the simulating strategy. The study of the behaviors of a particle settling in unbounded domain in viscous Newtonian fluid is presented in Section 4, while Section 5 focuses on the behaviors of a particle settling near a vertical wall as well as the comparison of a particle settling in unbounded domain and settling near a vertical wall. At the end, Section 6 is devoted to the summary and conclusions.

2. Numerical methods

2.1. Governing equations

The governing equations for the incompressible viscous Newtonian fluid immersed with particles are:

$$\nabla \cdot \boldsymbol{u} = 0 \tag{1}$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\nabla p + \frac{\rho}{\mu}\nabla^2 \boldsymbol{u} + \boldsymbol{g} + \boldsymbol{f} \tag{2}$$

where $\boldsymbol{u} = (u, v, w)$ is the velocity of fluid, p is the pressure. ρ and μ are the density and the viscosity of fluid, respectively. $\boldsymbol{g}$ represents the gravity, and $\boldsymbol{f} = (f_x, f_y, f_z)$ is the external force exerted on the fluid representing the mutual interactions between fluid and immersed particles.

The Newton's equations for the linear, angular momentum and transportation of a particle are as follows:

$$m_p \frac{d\boldsymbol{u}_p}{dt} = m_p \boldsymbol{g} + \boldsymbol{F} \tag{3}$$

$$\frac{d\boldsymbol{x}_p}{dt} = \boldsymbol{u}_p \tag{4}$$

$$I_p \frac{d\boldsymbol{\omega}_p}{dt} = \boldsymbol{T} \tag{5}$$

$$\frac{d\boldsymbol{\theta}_p}{dt} = \boldsymbol{\omega}_p \tag{6}$$

where m_p and I_p are particulate mass and inertial moment, respectively. $\boldsymbol{u}_p = (u_p, v_p, w_p)$ and $\boldsymbol{x}_p = (x_p, y_p, z_p)$ represent the velocity and position of the particulate mass center, while $\boldsymbol{\omega}_p = (\omega_{px}, \omega_{py}, \omega_{pz})$ and $\boldsymbol{\theta}_p = (\theta_{px}, \theta_{py}, \theta_{pz})$ are angular velocity and orientation of particle. $\boldsymbol{F}$ and $\boldsymbol{T}$ represent the hydrodynamic force and torque acting on the particle by the fluid, respectively.

2.2. Immersed boundary method and multi-direct forcing technique

By following the spirit of the direct forcing based on the Immersed Boundary method [19], f in Eq. (2) can be expressed as:

$$\boldsymbol{f}(\boldsymbol{x}) = \sum_{k=1}^{N} \boldsymbol{F}_k(\boldsymbol{x}_k) \cdot \delta(\boldsymbol{x} - \boldsymbol{x}_k)\Delta V_k \tag{7}$$

where $\boldsymbol{x}$ is the position of computational Eulerian mesh and $\boldsymbol{x}_k$ is the position of the Lagrangian point k set at the immersed boundary. N is the number of Lagrangian points on the boundary of each particle, and according to Uhlmann's [19] study, the principle to choose N is that $N \approx \frac{\pi}{3}\left[4\left(\frac{d_p}{h}\right)^2 + 1\right]$. Here d_p is the diameter of the particle and h is the computational mesh size. $\delta(\boldsymbol{x} - \boldsymbol{x}_k)$ is the Dirac delta function applied to spread the quantities between Eulerian grids and Lagrangian points, while ΔV_k represents the control volume of a Lagrangian point. $\boldsymbol{F}_k(\boldsymbol{x}_k)$ is the force exerted on the Lagrangian point $\boldsymbol{x}_k$. Based on Eq. (2), the external force $\boldsymbol{f}$ can be obtained from:

$$\boldsymbol{f} = \frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} + \nabla p - \frac{\rho}{\mu}\nabla^2 \boldsymbol{u} - \boldsymbol{g} = \frac{\boldsymbol{u}^{n+1} - \boldsymbol{u}^n}{\Delta t} - \boldsymbol{rhs} \tag{8}$$

where n and $n + 1$ represent two different time levels and

$$\boldsymbol{rhs} = -\left(\boldsymbol{u} \cdot \nabla \boldsymbol{u} + \nabla_p - \frac{\rho}{\mu}\nabla^2 \boldsymbol{u} - \boldsymbol{g}\right) \tag{9}$$

So for the fluid at $\boldsymbol{x}_k$, the force acting on the Lagrangian point can be calculated by:

$$\boldsymbol{F}_k(\boldsymbol{x}_k) = \frac{\boldsymbol{u}_k^{n+1} - \boldsymbol{u}_k^n}{\Delta t} - \boldsymbol{rhs} = \frac{\boldsymbol{u}_k^{n+1} - \hat{\boldsymbol{u}}_k}{\Delta t} + \frac{\hat{\boldsymbol{u}}_k - \boldsymbol{u}_k^n}{\Delta t} - \boldsymbol{rhs} \tag{10}$$

where $\hat{\boldsymbol{u}}_k$ is the intermediate velocity satisfying the pure momentum equation without $\boldsymbol{f}$, so $\frac{\hat{\boldsymbol{u}}_k - \boldsymbol{u}_k^n}{\Delta t} - \boldsymbol{rhs} = \boldsymbol{0}$ and

$$\boldsymbol{F}_k(\boldsymbol{x}_k) = \frac{\boldsymbol{u}_k^{n+1} - \hat{\boldsymbol{u}}_k}{\Delta t} = \frac{\boldsymbol{u}_L - \hat{\boldsymbol{u}}_k}{\Delta t} \tag{11}$$

here $\boldsymbol{u}_L$ is the desired velocity on the particle surface under the no-slip boundary condition.

The direct forcing exerted on the Lagrangian point can gradually modify the computational velocity $\boldsymbol{u}_k$ to the desired velocity $\boldsymbol{u}_L$, but as