Commun. Comput. Phys.
doi: 10.4208/cicp.311009.020910s

Vol. **9**, No. 5, pp. 1179-1192
May 2011

Behaviors of Spherical and Nonspherical Particles in a Square Pipe Flow

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Received 31 October 2009; Accepted (in revised version) 2 September 2010

Available online 28 January 2011

Abstract. The lattice Boltzmann method (LBM) for multicomponent immiscible fluids is applied to the simulations of solid-fluid mixture flows including spherical or nonspherical particles in a square pipe at Reynolds numbers of about 100. A spherical solid particle is modeled by a droplet with strong interfacial tension and large viscosity, and consequently there is no need to track the moving solid-liquid boundary explicitly. Nonspherical (discoid, flat discoid, and biconcave discoid) solid particles are made by applying artificial forces to the spherical droplet. It is found that the spherical particle moves straightly along a stable position between the wall and the center of the pipe (the Segré-Silberberg effect). On the other hand, the biconcave discoid particle moves along a periodic helical path around the center of the pipe with changing its orientation, and the radius of the helical path and the polar angle of the orientation increase as the hollow of the concave becomes large.

AMS subject classifications: 76D99, 76M28, 76T99, 76Z05

Key words: Lattice Boltzmann method, square pipe flow, spherical particle, biconcave discoid particle.

1 Introduction

Solid-fluid mixture flows are of interest not only in many engineering fields such as the handling of slurry, colloid, and ceramics, but also in biological fields in connection with blood flows in capillaries. In particular, the behaviors of nonspherical particles in a pipe flow are important in relation to the motions of red blood cells in blood flows. So far, the motions of spherical particles in a pipe flow have been investigated experimentally, theoretically, and numerically by many researchers.

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A particularly important experimental study on the motion of spherical particles in a pipe flow was performed by Segré and Siliberberg [1]. They discovered that neutrally buoyant particles in a pipe flow migrate laterally away both from the wall and the centerline and reach a certain equilibrium lateral position. Karnis et al. [2] verified the same phenomenon and observed that particles stabilize midway between the centerline and the wall, closer to the wall for larger flow rates and closer to the center for larger particles. They deduced that these phenomena are due to an inertia effect of the flow. Tachibana [3] found experimentally that the lateral migration of spheres in pipe flows depends mainly on the ratio of sphere diameter to the pipe diameter and that the phenomenon is clearly observed if this ratio exceeds about 0.2.

On the theoretical side, perturbation theories have been used to understand the lateral migration. Saffman [4] obtained the lift on a sphere particle in a shear flow in an unbounded domain. Ho and Leal [5] and Vasseur and Cox [6] investigated the lateral migration of a spherical particle in both a Couette flow and a plane Poiseuille flow bounded by two infinite plane walls. These theories for the bounded domain are valid for small channel Reynolds numbers. Schonberg and Hinch [7] extended Saffman's analysis to a small sphere in a Poiseuille flow for the channel Reynolds number of order unity, and McLaughlin [8] studied the lift on a small sphere in wall-bounded linear shear flows for small particle Reynolds numbers. Asmolov [9] investigated the inertial migration of a small rigid sphere translating parallel to the walls within a channel flow at large channel Reynolds numbers. In general, however, these perturbation theories can represent the motion of particles only subject to the severe restrictions that the Reynolds numbers be small and/or the particles be small, compared with the channel width.

On the other hand, numerical simulations have been used for the problem of particle motion in shear flows. Direct numerical simulations require no restrictions such as small Reynolds numbers, small particles, and so on. Thus, it is possible to compute the motion of particles not only around the center of a channel but also near a wall at various Reynolds numbers. Feng et al. [10] investigated the motion of a circular particle in a Couette and Poiseuille flow using a finite-element method and obtained qualitative agreement with the results of perturbation theories and of experiments. Nirschl et al. [11] carried out three-dimensional calculations of flows around a spherical particle between two moving walls using a finite-volume method with a Chimera grid scheme, but they were not concerned about the motion of the particle. Inamuro et al. [12] investigated the motions of a single and two lines of neutrally buoyant circular cylinders between flat parallel walls using the lattice Boltzmann method (LBM). Pan and Glowinski [13] carried out the direct simulations of the motion of neutrally buoyant balls in a three-dimensional Poiseuille flow using a Lagrange multiplier based fictitious domain method. From a numerical point of view, this subject is related to a moving boundary problem, and thus there are some difficulties in dealing with moving particles in a domain. Recently, in order to avoid the difficulties of the moving boundary problem, Inamuro and Ii [14] applied the LBM for multicomponent immiscible fluids with the same density to simulations of the dispersion of aggregated particles under shear flows with the Stokes flow approxima-