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Lateral migration of a spherical particle in channel flow

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In microfluidics, the migration of suspended particles perpendicular to the flow direction is gaining considerable attention due to a broad range of applications such as the filtration and separation of biological cells, although numerous phenomena related to lateral migration have long been known in other fields. For instance, it was observed in blood flow that red cells tend to migrate toward the vessel centerline, whereas platelets are displaced from the vessel centerline, plentiful in the vicinity of the vessel wall, and white cells marginate near the vessel wall in venules, especially under low-flow conditions. Another distinctive example is the so-called “Segré-Silberberg effect” observed for neutrally buoyant spherical particles in Poiseuille flow in circular tubes. Segré & Silberberg reported that rigid spheres migrate toward a radial position of about 0.6 tube radius from the tube axis at low Reynolds numbers [(1)]. This phenomenon is evidently due to the effect of inertia, since in the Stokes flow regime, a spherical particle translates parallel to the flow direction regardless of its radial position. Since the inertial migration behaviors depend on the particle size, their physical properties and the Reynolds number[(2)], the Segré-Silberberg effect has recently attracted substantial attention for invasive handling and effective separation of tissues and cells in the flow of microchannels as mentioned above. For such applications, the flow through channels of rectangular or square cross-sections is of great interest. In the present study, the lateral migration of rigid spherical particles in square channel flow has been investigated experimentally and numerically. In the experiment, we observed the distribution of particles at several cross-sections downstream from the channel entrance and examined the focusing properties toward the equilibrium positions. In the numerical study, we calculated the fluid force acting on the migrating particles and discussed the equilibrium position of the particles in the cross-section.

In the experiment, a mixture of water and glycerol suspending a small amount of spherical polystyrene beads of equal density were flowed in square channels. The observation of particle positions at channel cross-sections revealed the presence of several equilibrium positions of the particles at the center of the channel faces and at the corners, depending on the Reynolds number. The equilibrium positions were found to be independent of the distance of the cross-section from the channel entrance.

In the numerical computation, the fluid force acting on a single particle in a pressure-driven flow through a square channel of width H was calculated (Fig. 1). The no-slip condition was adopted on the channel walls (y, z=0, H) and the periodic boundary condition was applied at x=0, L. The numerical scheme is based on the method proposed by Kajishima *et al.*[(3)] The Navier-Stokes equation and continuity equation were time-integrated by the fractional step method. The momentum-exchange for the interaction between the fluid and particles was taken into account by considering the interacting force which is described in terms of the local solid volume fraction in each calculation cell. The total force and moment obtained by integrating the interacting forces over the volume of the particle were used to determine the particle movement based on Newton's equation of motion.

We examined the lateral (y and z directions) force acting on the particle which is prohibited from moving laterally but free to move in the flow direction (x direction) and to rotate. Figure 2 shows the force (f_y in the y direction and f_z in the z direction) acting on a sphere located along a line $z=H/2$ ($H/D=4.5$, $Re=8.8$, where D is the particle diameter). It is obtained that f_z is zero at any positions in the y direction, as would be expected from symmetry. On the other hand, f_y is positive near the channel wall (for small y/D) and negative near the channel center (for large y/D). The lateral position where the force vanishes is expected to be an equilibrium position. As seen in Fig. 2, the force distribution is in good agreement with previous numerical results [4]. In addition, we calculated trajectories of the particle which is released at various lateral positions and free to move in all directions. The results indicate that for initial release points near the equilibrium position shown in Fig. 2, the particle approaches progressively an asymptotic lateral position (square symbol in Fig. 2), which is coincident with the expected equilibrium position.

To summarize, the present numerical simulation indicates that there are positions where the force acting on the particle vanishes and these positions correspond to the equilibrium positions where the particles are observed to focus in the experiments.

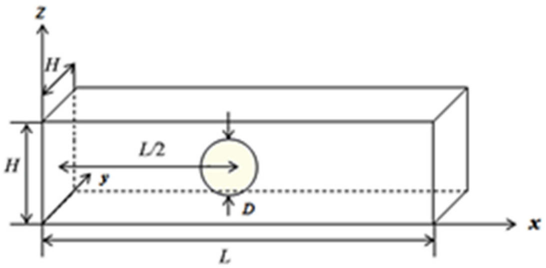

Fig. 1 Computational domain for the simulation of a sphere in channel flow (H: channel width, L: channel length, D: particle diameter).

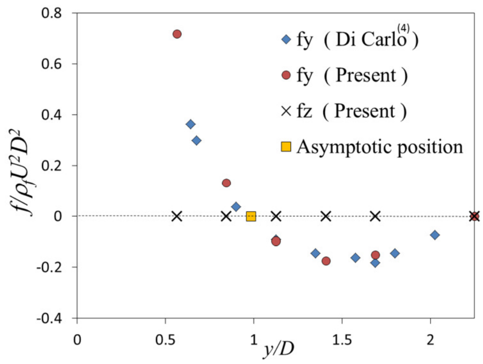

Fig. 2 Normalized force acting on a sphere located along a line $z=H/2$ ($H/D=4.5$, $Re=\rho_f UD/\mu$ $=8.8$). ρ_f is the fluid density, μ is the viscosity and U is the mean flow velocity in the channel.

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