Cross-stream inertial migration of rigid microparticles in a pressure-driven flow of a power-law fluid

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1. Introduction

Separation and focusing of cells are critical processes in biomedical applications [1-4]. In these applications, the samples of interest are mostly composed of various populations of cells with different sizes, shapes, and properties needed to be isolated, filtered, or sorted. These operations are considered as critical tasks in many areas of biology, biotechnology, and medicine and are used for diagnostic, therapeutic, or biological purposes [5]. There are several techniques that use biochemical markers for separation of cells in a heterogeneous population such as Fluorescence-activated cell sorting (FACS) [6] and Magnetic-activated cell sorting (MACS) [7]. However, because these techniques are complex and require high cost procedures, researchers focus on the development of label-free strategies, which rely on the intrinsic properties of the cells and the physical properties of the fluid using microfluidic devices. One of the approaches to achieve size-based separation of biological and synthetic particles is based on the inertial cross-stream migration of particles within microchannels with a pressure driven flow. Here we use computational modeling to examine cross-stream migration of microparticles in a microchannel filled with a generalized Newtonian fluid.

2. Methods

Using three-dimensional computer simulations, we examine the inertial migration of a rigid spherical particle in a power-law fluid in microfluidic channels. We employ a hybrid computational approach [8-9] to model the dynamic interactions between a rigid particle and a viscous channel flow. Our approach integrates the lattice Boltzmann model (LBM) for the dynamics of viscous fluids and the lattice spring model (LSM) to describe the dynamics of solid particles. The two models are coupled through appropriate boundary conditions at the movable solid-fluid interface.

The LBM is a lattice-based numerical method for simulating hydrodynamic flows governed by the Navier-Stokes equations. The method is based on the time integration of a discretized Boltzmann equation for a particle distribution function [10-11]. In three dimensions, LBM is characterized by a 19-velocity distribution function, describing the mass density of fluid particles propagating along a specific lattice direction. The hydrodynamic quantities are calculated as moments of the distribution function. The solid material of particle’s shell is represented by a LSM [12-13]. By using the Delaunay triangulation technique [14], we distribute nodes uniformly on the spherical particle surface. We use an interpolation bounce-back rule [15] that is applied to the LBM distribution functions that cross the surface of the solid particle.

For the problem setup, we consider a rectangular computational domain filled with a power-law viscous fluid driven by a pressure gradient. The top and bottom walls of the domain are stationary and represent the microchannel walls. We impose periodic boundary conditions on the rest of domain boundaries. The geometry of the channel can be modified by adding square ridges attached to the walls to probe particle motion in a diverging-converging microchannel.

3. Results

We study the dynamics of particles moving in a generalized Newtonian fluid. The equilibrium positions and the migration velocity of a single particle in the channel flow are examined for different flow rates and different particle-channel size ratios. We first validate our model by comparing the cross-stream particle velocity in a Newtonian fluid at Re=1 by comparing our compactional results with the theoretical results [16] (Figure 1).

To examine the effect of shear dependent fluid viscosity on cross-stream inertial migration, we simulate the motion of particles in a power-law fluid with power-law different exponents. We find that cross-stream velocity strongly depends on the fluid exponent n. Figure 1 shows normalized cross-stream velocity for fluids with n=0.5 and n=1.5 as a function of the distance from the wall in a channel with a particle-channel aspect ratio of 1/60. Furthermore, the simulations show that the equilibrium positions for different fluid exponents can vary significantly. It is found that the particle equilibrates towards the center in a shear thickening fluid. On the other hand, in a shear thinning fluid the equilibrium position is
shifted closer to the wall with an additional equilibrium position emerging near the channel centerline (see the inset in Figure 1). The later effect is promising for high resolution separation of particles that can focus, depending on the properties, at very distinct equilibrium positions near the wall or near the channel centerline.

4. Conclusions

Using three-dimensional computer simulations, we examine cross-stream migration of particles in a generalized Newtonian fluid. The results show particle equilibration strongly depends on fluid properties, which can be used for separation of biological particles in biomedical applications.

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References


Figure 1. Cross-stream migration velocity of rigid spherical particles in power-law fluids with different fluid exponent