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RESEARCH PAPER

Three-dimensional and analytical modeling of microfluidic particle transport in magnetic fluids

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Abstract We present an analytical model that can predict the three-dimensional (3D) transport of non-magnetic particles in magnetic fluids inside a microfluidic channel coupled with permanent magnets. The magnets produce a spatially non-uniform magnetic field that gives rise to a magnetic buoyancy force on the particles. Resulting 3D trajectories of the particles are obtained by (1) calculating the 3D magnetic buoyancy force exerted on the particles via an analytical distribution of magnetic fields as well as their gradients, together with a nonlinear magnetization model of the magnetic fluids, (2) deriving the 3D hydrodynamic viscous drag force on the particles with an analytical velocity profile of a low Reynolds number ferrohydrodynamic flow in the channel including "wall effect" and magnetoviscous effect of the magnetic fluids, and (3) constituting and solving the governing equations of motion for the particles using the analytical expressions of magnetic buoyancy force and hydrodynamic viscous drag force. We use such a model to study the particles' trajectories in the channel and investigate the magnitude of their deflections at different flow rates, with different properties of magnetic fluids and different geometrical parameters of the system.

Keywords Microfluidics · Particle transport · Magnetic fluids · Ferrofluids · Three-dimensional · Particle separation

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1 Introduction

Microfluidic particle transport has generated a lot of enthusiasm in the past decade for its potential applications in diagnostics (Nagrath et al. 2007; Adams et al. 2008; Hoshino et al. 2011; Mao and Huang 2012b), therapeutics (Toner and Irimia 2005; Yung et al. 2009) and environmental monitoring (Liu et al. 2004; Beyor et al. 2008; Dharmasiri et al. 2010). Techniques developed to transport particles and cells so far were mainly based on their intrinsic physical properties for manipulation specificity (Pamme 2007; Tsutsui and Ho 2009; Gossett et al. 2010; Lenshof and Laurell 2010; Robert et al. 2011; Mao and Huang 2012a; Tarn et al. 2013). Thanks to their high throughput, low-cost and lacking of labeling steps in most cases, these techniques were often preferred over existing label-based macro-scale techniques such as fluorescence-activated sorter (FACS) (Bonner et al. 1972). Among them, those based on passive microchannel geometry including pinched flow fractionation (Yamada et al. 2004) and deterministic lateral displacement (Huang et al. 2004; Davis et al. 2006) combined laminar flows with micro-channel structures to direct particles of different sizes or deformability (McFaul et al. 2012) into separate streamlines. At the same time, external energy inputs including acoustic, electric and magnetic forces have also been used for manipulations. For instances, acoustophoresis was used to separate particles and cells according to their size, density, as well as compressibility (Laurell et al. 2007; Shi et al. 2009; Wang and Zhe 2011). Dielectrophoresis (DEP) realized low-cost and integrated devices for cell manipulation (Voldman 2006; Pethig 2010). Magnetophoresis was applied to separate paramagnetic red blood cells or bacteria from other species (Zborowski et al. 2003; Lee et al. 2004). Magnetophoresis is a label-based technique (Pamme 2006;

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