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Drop formation of ferrofluid at co-flowing microcahnnel under uniform magnetic field

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ABSTRACT

A hybrid lattice-Boltzmann, with Shan–Chen model, and finite volume method is applied to simulate the effect of magnetic field on ferrofluid drop formation in Co-flowing configuration of non-magnetic viscous media, in microchannels. The lattice Boltzmann method is used to track the moving interface between the two immiscible phases, and to update the flow field by adding magnetic field force in lattice Boltzmann equations. Maxwell's equations are solved by finite volume method to obtain the magnetic field. The accuracy of the present method is checked with previous numerical and experimental investigations. The comparison indicates that the present results are in good agreement with previous research in the literature. The effects of the flow rate ratio, magnetic Bond number, and susceptibility on the length of drop, the distance between drops and frequency of drop generation in Co-flowing microchannels are investigated in detail. The results reveal that a magnetic field can be used to control drop size, distance between drops, and drop formation frequency effectively. The outcome of this study further point out, a hybrid lattice-Boltzmann, with Shan–Chen model-finite volume method is an effective way to simulate drop formation in microchannels under the action of magnetic field.

1. Introduction

Drop formation in microchannels has found widespread applications in area such as cell encapsulation [1], microchemical analysis [2], crystallization of proteins [3], and DNA analysis [4]. There exist different geometries for drop formation in microchannels. Some of this geometries, for example, are T-junction [5], Co-flowing [6], cross junction [7], and flow focusing [8]. Mixing geometry, flow rates of the two immiscible fluids, and fluid properties are the most important criteria to control the drop size and the drop formation frequency in a microchannels. A number of experimental and numerical studies have been performed to investigate the effects of flow conditions on drop formation in the mixing of two immiscible fluids in microchannels [5–13].

Numerous techniques can be used for manipulating drops actively; such as nonuniform temperature field [14], thermocapillarity [15] and electrowetting [16]. Applying external magnetic field is an effective and contactless way to control drop movement. When a ferrofluid drop, in another fluid with different magnetic properties, was exposed to magnetic field, the ferrofluid drop deforms. Ferrofluids consist of ferromagnetic nanoparticles coated with a layer of surfactants and suspended in a non magnetic carrier liquid [17]. Rosensweig explained the mathematical formulation for hydrodynamics of ferrofluid [17] and simulated manipulation of a ferrofluid drop in a uniform magnetic field by coupling the free surface, the magnetic field, and the fluid flow. Korlie et al. [18] investigated falling of a ferrofluid drop in a non-magnetic medium, numerically. Afkhami et al. [19] simulated the deformation of non-linear magnetic ferrofluid drop in the non-magnetic fluid. Tan et al. [5] studied the effects of the magnetic field strength on fluid flow into microfluidic T-junction geometry. Liu et al. [8] examined the formation process of ferrofluid drops in a flow focusing microchannel with and without an applied magnetic field. This was done both numerically and experimentally. Wu et al. [7] implemented both uniform and non-uniform magnetic fields to control actively breakup of ferrofluid in T-junction.

Recently, the lattice Boltzmann method (LBM), which is based on mesoscopic kinetic equations, has been proven to be a promising, numerically robust, technique to simulate complex flows. Some examples of these flows are natural convection [20–22], nanofluids [22], non-Newtonian fluids [23], unsteady flow [24] and flow of two immiscible phases in complex geometries [25]. Compared with conventional methods for multiphase flows, LBM does not track interfaces while sharp interfaces can be maintained automatically [25]. LBM based immiscible multiphase flow

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model can be divided into four types: the intermolecular interaction model [26], the Pseudo-Potential model (Shan–Chen model) [27,28], the Chromo-dynamic model [29], and the free-energy model [30]. Among these models the Shan–Chen model is the widely model used, due to its simplicity and adaptability. Montessori et al. [31] applied three-dimensional Lattice Pseudo-Potentials to simulate multiphase flows at high density ratios. They showed that the combination of generalized Van der Waals equations of state with high-order discrete velocity lattices, permits to simulate the dynamics of liquid droplets at air–water density ratios, with very moderate levels of spurious currents near the droplet interface. Fallah et al. [12] and Fallah and Taeibi [13] numerically studied the drop formation microchannels using the lattice Boltzmann method based on the Pseudo-Potential method. They showed that the Pseudo-Potential lattice Boltzmann method is an effective way to simulate the generation of drops in microchannels. Falcucci et al. [32] presented a nonisotropic extension of the single-component Shan–Chen model for nonideal fluids, which is capable of modeling the deformation of a magnetic droplet. With comparing experimental data, they concluded that their method is able to capture relevant features of ferrofluid behavior, such as the deformation and subsequent rupture of a liquid droplet as a function of an externally applied magnetic field.

To the authors' best knowledge, simulation of ferrofluid drop formation in Co-flowing microchannels fluid under the uniform magnetic field in two-phase flow is not studied yet. This work reports the development of a 2-D numerical model to simulate the formation process of ferrofluid drops in a non-magnetic fluid in a Co-flowing configuration under a uniform magnetic field. To this approach, a hybrid lattice-Boltzmann with Shan–Chen model and finite-volume method is implemented. The lattice Boltzmann method was used to track the moving interface between the two immiscible phases, and to update the flow field by adding magnetic field force in LB equations. Maxwell's equations are solved by finite volume method to obtain the magnetic field. The effects of the flow rate ratio, magnetic Bond number, and susceptibility in Co-flowing microchannels are investigated in detail.

2. Mathematical models

2.1. Magnetic field equations

The Maxwell's equations for non-conducting fluids are [33]:

$$\nabla \times \mathbf{H} = 0, \tag{1}$$

$$\nabla . \mathbf{B} = 0, \tag{2}$$

$$\mathbf{B} = \begin{cases} \mu_0 (\mathbf{H} + \mathbf{M}) \text{ in the ferrofluid } (\Omega_\mathrm{d}) \\ \mu_0 \mathbf{H} \text{ in the viscous medium } (\Omega_\mathrm{c}), \end{cases} \tag{3}$$

where, **H**, **B**, and **M** denote the magnetic field, the magnetic induction, and the magnetization of the ferrrofluid, respectively. $\mu_0 = 4\pi \times 10^{-7}\mathrm{N/A}^2$ is the permeability of vacuum. The magnetization of the ferrrofluid (**M**) is assumed to be a linear function of the magnetic field by assuming $\mathbf{M} = \chi \mathbf{H}$; Where $\chi = (\mu_d/\mu_0 - 1)$ is the magnetic susceptibility. Thus, the magnetic induction inside the ferrofluid is given by $\mathbf{B} = \mu_1 \mathbf{H}$; Where μ_1 is the magnetic permeability of the ferrofluid. By combining Eqs. (1)–(3) and introducing the magnetic scalar potential $\varnothing$ in the form of $\boldsymbol{H} = -\nabla\varnothing$ yields [33]:

$$\nabla . [\mu \nabla \varnothing] = 0. \tag{4}$$

The permeability jumps across the interface between two immiscible phases. As a result, the scalar potential varies as the interface is moving. Thus, the magnetic permeability can be expressed as follow [33]:

$$\mu_\varepsilon (\varnothing) = \mu_\mathrm{d} H_\varepsilon (\varnothing) + \mu_\mathrm{c} (1 - H_\varepsilon (\varnothing)), \tag{5}$$

where, the subscripts c and d refer to the nonmagnetic and ferrofluid phases, respectively. $H_\varepsilon (\varnothing)$ is the modified Heaviside function and is defined as [33]:

$$H_\varepsilon (\lambda) = \begin{cases} 0 & \text{if } \rho = \rho_1 \\ \dfrac{1}{2}\left[1 + \lambda + \dfrac{1}{\pi}\sin(\pi\lambda)\right] & \text{if } \rho_1 < \rho < \rho_2 \\ 1 & \text{if } \rho = \rho_2, \end{cases} \tag{6}$$

where, λ is a parameter and defined as:

$$\lambda = \frac{\rho_1}{\rho_1 + \rho_2}, \tag{7}$$

In order to obtain magnetic field, first, the magnetic potential should be obtained by numerically solving Eq. (4). The magnetic potential, Eq. (4), is discretized on the Cartesian uniform grid by finite volume method, using second-order central difference scheme. The central difference equation is subsequently solved, using ADI method.

2.2. Shan and Chen model

In this study, the multi-component lattice Boltzmann model proposed by Shan and Chen [27] is applied to simulate ferrofluid drop falling in a vertical channel. The distribution functions of the lattice Boltzmann equation using the single relaxation time collision for multiphase flow is:

$$f_i^\sigma (\boldsymbol{x} + \boldsymbol{e}_i \delta t, t + \delta t) = f_i^\sigma (\boldsymbol{x}, t) - \frac{f_i^{\sigma\,(eq)} - f_i^\sigma}{\tau^\sigma}, \tag{8}$$

where, f_i is the particle distribution function of component σ along the ith-direction, δt is time step size, and. f^{eq} is equilibrium distribution function of f, and given by:

$$f_i^{\sigma\,(eq)} = w_i \rho^\sigma \left[1 + \frac{\boldsymbol{e}_i \boldsymbol{u}_{eq}^\sigma}{c_s^2} + \left(\frac{\boldsymbol{e}_i \boldsymbol{u}_{eq}^\sigma}{2c_s^4}\right)^2 - \frac{\boldsymbol{u}_{eq}^\sigma \boldsymbol{u}_{eq}^\sigma}{2c_s^2}\right], \tag{9}$$

where, $\boldsymbol{e}_i$ denotes the particle velocity in the ith direction, defined as follows for D2Q9:

$$\boldsymbol{e}_i = \begin{cases} (0, 0) & i = 0 \\ \left(\cos\left[\dfrac{(i-1)\pi}{4}\right], \sin\left[\dfrac{(i-1)\pi}{4}\right]\right) c & i = 1, 2, 3, 4 \\ \sqrt{2}\left(\cos\left[\dfrac{(i-1)\pi}{4}\right], \sin\left[\dfrac{(i-1)\pi}{4}\right]\right) c & i = 5, 6, 7, 8, \end{cases} \tag{10}$$

where, w_i are weighting factors for each velocity ($w_0 = 4/9$, $w_i = 1/9$ for $i = 1$–4, and $w_i = 1/36$ for $i = 5$–8). The macroscopic density ρ and velocity $\boldsymbol{u}$ in the lattice unit for each component are obtained from:

$$\rho^\sigma = \sum_{i=0}^{8} f_i^\sigma, \; u^\sigma = \sum_{i=0}^{8} \frac{\boldsymbol{e}_i f_i^\sigma}{\rho^\sigma}. \tag{11}$$

In the multicomponent model for each component, $\boldsymbol{u}_{eq}^\sigma$, appearing in Eq. (9) is given by:

$$\boldsymbol{u}_{eq}^\sigma = \boldsymbol{u}' + \frac{\tau^\sigma \mathbf{F}^\sigma}{\rho^\sigma}, \tag{12}$$

where, τ^σ is the relaxation time of component σ which relates to kinematic viscosity as $\mu^\sigma = (\tau^\sigma - 0.5)\, c_s^2 \delta t$. $\boldsymbol{u}'$ is velocity common to the various components defined as:

$$\boldsymbol{u}' = \frac{\sum_{\sigma=1}^{2} \frac{\rho^\sigma u^\sigma}{\tau^\sigma}}{\sum_{\sigma=1}^{2} \frac{\rho^\sigma}{\tau^\sigma}}. \tag{13}$$

$\mathbf{F}^\sigma$ appearing in Eq. (12) is the total interaction force exerted on the σth component. It includes expressed as including fluid–fluid