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Flow and heat transfer performances of dilute magnetorheological fluid flowing through hot micro channel

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The thermal lattice Boltzmann method (TLBM) with doubled-population is used to analyze the dilute magnetorheological fluid (MRF) flow and heat transfer performances in two-dimensional hot micro channels, by regarding the magnetic particles (MPs) as a quasi fluid. A method for calculating external forces on MPs is established in order to improve the computational accuracy and efficiency. It is revealed that with the increasing volume fraction of MPs, on lattice node, both the Van der Waals force and the magnetic dipole force increase but the Brownian force only randomly varies within a range which is three orders of magnitude smaller than magnetic dipole force. Simulations are carried out under both constant temperature and heat flux boundary conditions. The effects of channel length, inlet velocity and volume fraction of MPs on heat transfer performances are investigated and the results indicate that the dilute MRF behaves a better heat transfer performance than water even without the effect of external magnetic field.

1. Introduction

Microfluidic structures are used for various mechanical, chemical and biochemical determinations. These structures contain channels, mixers, pumps, sensors, heaters and have many applications in biochemical and clinical analysis, in separation or detection of chemical substances. Application of miniaturised system enables operation of integrated modules (lab on a chip), and makes possible reduction of time and cost of the analysis due to using small amounts of a sample and reagents. The primary task is to quantify the heat and mass transport to support kinetic studies in this type of structures [1]. The microchannel heat sink has brought significant improvements in the cooling performance of many instruments with high heat productivity. The structure design and optimization of microchannel heat sink have been well developed in recent years. Circular and rectangular channels are the two representative flow channels to deliver cooled or heated fluids [2], and some other forms, such as triangle and trapezoidal channels [3], are also used in the construction of heat sinks. To enhance the heat transfer capability, nanofluids are used to substitute common single-phase medium because they can reduce the temperature difference between the hot surface of heat sink and nanofluid compared with that from pure fluid [4–6].

Nanofluids, using nanoscale particles dispersed in a base fluid, are invented to enhance the performance of conventional heat transfer. Nanocomposites with magnetic properties, which use magnetic nanoparticles inserted in dielectric matrices, are of considerable technological importance. Magnetorheological fluids (MRFs) are suspensions of magnetizable particles (e.g. magnetite particles, MPs) in nonmagnetizable base fluids, such as water or oil. In more recent years new products have been developed for medical, military and industrial applications. The main advantage of the use of magnetofluids as the thermal transfer medium is based on the response of magnetic particles to external magnetic field so that the fluid presents anisotropic heat transfer capability. It was found that the influence of magnetic field can be diminished by reducing the angle between the flow direction and the direction of magnetic field [7]. It has been experimentally validated that the overall efficiency of the heat sink using MRF is improved by 45% and when an alternating magnetic field was applied [8].

If MRF is regarded as a uniform medium, finite volume method can be adapted to simulate momentum and magnetic coupled equations of a laminar magnetic fluid flow [9,10]. But the structures composed of MPs in MRF usually play dominant role in the heat and mass transport in micro systems. From the microscopic point of view, the existing traditional computational methods for

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Nomenclature

A	Hamaker constant
$\mathbf{c}$	Lattice velocity vector
c_p	Specific heat
D	Equivalent diameter of micro groove
d	Diameter of MPs
$\mathbf{F}$	External force on lattice point
F_g	Resultant force of gravity and buoyancy
F_d	Stokesian force
F_v	Van der Waals force
F_m	Magnetic dipole force
F_b	Brownian force
f, g	Population functions for density-momentum and internal energy
f^{eq}, g^{eq}	Equilibrium functions for f and g
G	Acceleration of gravity
h	Volumetric heat transfer coefficient between MPs and base fluid
k	Thermal conductivity
k_B	Boltzmann constant
l	Length of microchannel
l_s	Surface spacing of two particles
$\mathbf{M}$	Vector of magnetic moment of MP
$\mathbf{n}$	Unit vector of magnetic moment
$\mathbf{r}$	Coordinate vector
r	Radius of MP
r_{ab}	Distance between two MPs a and b
S	Total superficial area of MPs in a lattice volume
T	Temperature
Δt	Time step
$\mathbf{u}$	Velocity vector
$\mathbf{v}_p$, $\mathbf{v}_f$	Velocity vectors of MP and base fluid
Δv	Velocity difference between MP and base fluid
u, v	Velocity components along the x- and y-axis
w	Width of microchannel
Δx	Lattice spacing
Z	Effect of viscous heating

Greek symbols

ε_v, ε_T	Tolerances of velocity and temperature
μ	Kinetic viscosity
μ_0	Vacuum permeability
v	Kinematic viscosity
ρ	Density
τ_f, τ_g	Momentum and internal energy relaxation time
ω	Weighting coefficient in lattice
$\Delta\rho$	Density difference between base fluid and MP
φ	Volume fraction

Subscript

f	Base fluid
k	Lattice direction
p	MP
w	Wall
in	Inlet of channel

Superscript

*	Dimensionless parameter

conventional two-phase fluids fail to reveal the inherent nature of the flow and energy transport process inside the nanofluids. To achieve the micro details, numerical methods, such as the Monte Carlo (MC) simulation, Molecular Dynamics (MD) simulation and lattice Boltzmann simulation, have been used to study the microstructural transformation of MR fluids [11–13]. To obtain the detailed information of the motion of nano particles, the most accurate approach might be MD simulation, where the particle-particle and particle-fluid interactions are considered at molecular scale. However, MD simulations may not be suitable for MRF because of the scale difference between MP and base fluid. Another strategy for dealing with the MR fluid interactions is to use the Stokesian dynamics (SD) simulation method, where the drag force on MPs is evaluated using the Stokes's law [14]. But for a micro-scale flow system, SD simulation encounters a fatal problem of large amount of calculation while dealing with huge number of equations of motion for all MPs.

A microscopic or mesoscaled approach should be introduced to describe the effects of interactions between the suspended nanoparticles and liquid particles as well as among the solid particles. A lattice Boltzmann model for simulating flow and energy transport processes inside nanofluids was established in the light of the generalized algorithm proposed by Shan and Doolen [15]. In order to consider the interaction between MPs and base fluid, the lattice Boltzmann method (LBM) is employed in this work. LBM has been widely used in dealing with single phase flow. If thermal diffusion should be considered, a thermal Lattice Boltzmann method (TLBM) with doubled-population is usually used. A thermal lattice BGK model with doubled-population, together with a new boundary condition for temperature and heat flux, was proposed to simulate the two-dimensional natural convection flow in a cavity [16], and it was also used to simulate the laminar mixed convective heat transfer in two dimensional rectangular inclined driven cavity [17]. By coupling the density and the temperature distribution functions, the convection heat transfer utilizing Al_2O_3-water nanofluid in a square cavity was simulated, and in this work the nanofluid was treated as a single phase fluid [18].

If MRF is taken as a multi-phase fluid, it is necessary to consider the interactive forces among MPs and base fluid. But consider the large number of MPs in microscale flow, it is impossible to establish equations of motion for all MPs. Ladd proposed a method to regard the discrete MPs as a quasi fluid so that the solid phase can also be simulated using LBM with doubled populations [19]. By accounting for the external and internal forces acting on the suspended nanoparticles and interactions among the nanoparticles and fluid particles, a lattice Boltzmann model was proposed for simulating flow and energy transport processes inside the nanofluids [20]. This method was used to investigate the natural convection of nanofluid [21] and in this method, the boundary unknown energy distribution functions can be made functions of known energy distribution functions and correctors [22]. A thermal lattice Boltzmann flux solver (TLBFS) was developed for simulation of incompressible thermal flows. In TLBFS, the TLBM is only applied to reconstruct the local solution of TLBM for evaluation of fluxes at the cell interface [23]. Slip velocity and temperature jump can also be considered in LBM simulation [24].The development and application of LBM and TLBM have shown that it is a highly efficient method for investigating heat and mass transfer of nanofluids.

In this work, the TLBM with doubled-population is employed to investigate the flow and heat transfer performances of dilute MRF in hot microchannel. To consider the density change of MPs in the microchannel and its effect on the heat and mass transfer performances, the solid phase (MPs) is taken as a quasi fluid which is also governed by the doubled-population equations. A method to