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Three dimensional lattice Boltzmann simulation for mixed convection of nanofluids in the presence of magnetic field

Wenning Zhou [a,*], Yuying Yan [b], Yulei Xie [a], Baiqian Liu [a]

[a] School of Energy and Environmental Engineering, University of Science and Technology Beijing, Beijing 100083, China
[b] Fluids and Thermal Engineering Research Group, Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK

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ABSTRACT

In the present study, a three dimensional thermal lattice Boltzmann model was developed to investigate the flow dynamics and mixed convection heat transfer of Al_2O_3/water nanofluid in a cubic cavity in the presence of magnetic field. The model was first validated with previous numerical and experimental results. Satisfactory agreement was obtained. Then the effects of Rayleigh number, nanoparticle volume fraction, Hartmann number and Richardson number on nanofluid flow dynamics and heat transfer were examined. Numerical results indicate that adding nanoparticles to pure water leads to heat transfer enhancement for low Rayleigh numbers. However, this enhancement might be weakened and even reversed for high Rayleigh numbers. In addition, the results show the external applied magnetic field has an effect of suppressing the convective heat transfer in the cavity. Moreover, the results demonstrate that the Richardson number in mixed convection has significant influences on both streamlines and temperature field.

1. Introduction

Natural/mixed convection heat transfer in a cavity has been the subject of investigation due to its numerous practical applications including heat exchangers, solar collectors, nuclear reactors, energy systems, and many others [1,2]. Traditional fluids such as water, ethylene glycol and mineral oils usually have low thermal conductivities. To enhance thermodynamic performance, nanofluids, a suspension of nanoparticles into base fluids, possess high thermal conductivity and have been considered as a promising solution [3,4]. Extensive research has been carried out in this area. Experimental work reported that the thermal conductivity is enhanced by 30% for carbon nanotube nanofluids (2 vol%) [5]; and heat transfer enhancement up to 40% has been obtained for Al_2O_3/water nanofluid and Al_2O_3/ethylene glycol nanofluid compared to the base fluid [6]. Zhai et al. [7] carried out experiments to study heat transfer enhancement of Al_2O_3/water nanofluid through a micro heat sink with complex structure. Their results showed that higher volume fraction of nanofluids (0.1–1 vol%) gives better comprehensive performance of heat transfer.

Recently the effect of external magnetic field on the heat transfer of nanofluids has also received great attention due to their various applications in many fields such as crystal growth, microelectronic devices, medical science, and so forth [8]. Sheikholeslami et al. [9] applied the control volume based finite element method (CVFEM) to simulate magnetohydrodynamics (MHD) natural convection heat transfer between a circular enclosure and an elliptic cylinder. They concluded that the average Nusselt number increases with the increasing of nanoparticle volume fraction and Rayleigh number, but it decreases with the augment of Hartmann number. A meshless point collocation method was developed to investigate MHD natural convection flow in an inclined square enclosure [10]. Their results showed both the strength and orientation of the magnetic field have significant effects on the flow and temperature fields. Selimefendigil et al. [11] recently used the finite element method to study mixed convection entropy generation of CuO/water nanofluid under the influence of inclined magnetic fields. They found that the average Nusselt number decreases with the increasing of Richardson number and Hartmann number. A finite difference scheme was developed to investigate MHD mixed convection over an isothermal circular cylinder in the presence of an aligned magnetic field [12]. They claimed that the fluid flow with large mixed convection can be better controlled with the help of external applied magnetic field.

In the past decade, the lattice Boltzmann method (LBM) has been proposed as a powerful numerical tool for simulating complex multiphase flow [13,14], electoosmotic flows [15,16], heat transfer [17,18], reactive transport [19], and so forth. One can refer to the recent reviews in this area [20–22]. The kinetic nature of LBM gives it many advantages including the simplicity of programming, the parallelism of the algorithm and the capability of incorporating complex microscopic interactions [20]. The LBM has recently been extended to simulate nanofluids flow and heat transfer phenomena [23]. A LES-based lattice Boltzmann

* Corresponding author.
E-mail address: wenningzhou@ustb.edu.cn (W. Zhou).

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was proposed to study the heat and mass transfer mechanism of double diffusive natural convection of nanofluid from laminar regimes to turbulent regimes [24]. Ahrar et al. [25] applied the lattice Boltzmann method to investigate a nanofluid filled cavity with sinusoidal temperature boundary condition under the influence of an inclined magnetic field. They found that the influence of nanoparticles for this geometry and boundary condition is highly dependent to Rayleigh and Hartmann numbers. A MRT thermal lattice Boltzmann model was developed to simulate MHD flow and heat transfer of Cu/water nanofluid in an inclined cavity with four heat sources [26]. The results showed that the volume fraction of nanoparticles, Hartmann number and inclination angle of cavity have great influences on flow dynamics and heat transfer. Mahmoudi et al. [27] studied natural convection cooling of a nanofluid subjected to a magnetic field in a cavity with two heat sinks vertically attached to the horizontal walls. They found that the heat sinks positions greatly influence the heat transfer rate. Sheikholeslami et al. [28] conducted a numerical investigation on the effect of horizontal magnetic field on free convection heat transfer in a concentric annulus filled with Al_2O_3/water nanofluid. The results showed that the average Nusselt number increases with the increasing of nanoparticle volume fraction and Rayleigh number, but opposite trend is observed when Hartmann number increases. Chen et al. [29] used the lattice Boltzmann method to investigate the natural and mixed convection of Al_2O_3/water nanofluid in a square enclosure. They found that adding nanoparticles on the properties of nanofluids is enlarged in mixed convection situation. Despite a number of studies on nanofluid heat transfer enhancement have been carried out, most of them were conducted in a 2D model for natural convection. There is still a lack of information regarding MHD mixed convection in a cubic cavity. Therefore, in order to accurately investigate natural/mixed convection of nanofluids, a 3D lattice Boltzmann model for MHD mixed convection heat transfer is desirable.

In this work, we extend our previous studies on nanofluids [30,31] to investigate mixed convection of nanofluids in the presence of magnetic field in a cubic cavity by developing a 3D LBM model. The effects of Rayleigh number, nanoparticle volume fraction, Hartmann number and Richardson number on nanofluid flow and heat transfer have been examined in this study. The rest of this paper is organized as follows: Section 2 introduces mathematic formulation for nanofluid and lattice Boltzmann method. Grid independence and code validation are presented in Section 3. Numerical results and discussion for MHD natural/mixed convection heat transfer are included in Section 4. The conclusions are drawn in Section 5.

2. Problem description and mathematic formulation

2.1. Problem description

The schematic of the physical model is illustrated in Fig. 1. The length of each side of the cubic cavity is L. The hot wall and cold wall are located at $X=0$ and $X=1$, respectively. The other walls of the investigated domain are assumed to be adiabatic. An external magnetic field with uniform strength B_0 is applied. The orientations of the magnetic field with X axis and Z axis are θ_x and θ_z, respectively. The cavity is filled with Al_2O_3/water nanofluid.

2.2. Lattice Boltzmann method

The LBM method with standard three dimensional, nineteen velocities (D3Q19) model for both flow field and temperature is employed in this work. For the sake of completeness, a brief introduction of lattice Boltzmann method is included. One can refer to Refs [32,33] for more details. The discretized LBM equations for flow and temperature field can be written as:

$$f_i(x+c_i\Delta t, t+\Delta t) = f_i(x,t) - \frac{1}{\tau_\nu}\left(f_i(x,t) - f_i^{eq}(x,t)\right) + \Delta t F_i \quad (1)$$

$$g_i(x+c_i\Delta t, t+\Delta t) = g_i(x,t) - \frac{1}{\tau_\alpha}\left(g_i(x,t) - g_i^{eq}(x,t)\right) \quad (2)$$

where c_i denotes the discrete particle velocity vectors, Δt is the lattice time step which is set to unity. F_i is the external force term in the direction of lattice velocity. τ_ν,τ_α are the relaxation time for the flow and temperature field which are related to kinetic viscosity and thermal diffusivity, i.e., $\nu = (\tau_\nu - 1/2)c_s^2\Delta t$ and $\alpha = (\tau_\alpha - 1/2)c_s^2\Delta t$. f_i^{eq},g_i^{eq}represent the local equilibrium distribution functions for flow and temperature field which can be calculated by:

$$f_i^{eq} = \rho w_i\left[1 + \frac{c_i \cdot u}{c_s^2} + \frac{(c_i \cdot u)^2}{2c_s^4} - \frac{u \cdot u}{2c_s^2}\right] \quad (3)$$

$$g_i^{eq} = w_i T\left[1 + \frac{c_i \cdot u}{c_s^2}\right] \quad (4)$$

where c_s is the lattice speed of sound which is equal to $c_s = c/3$, and the

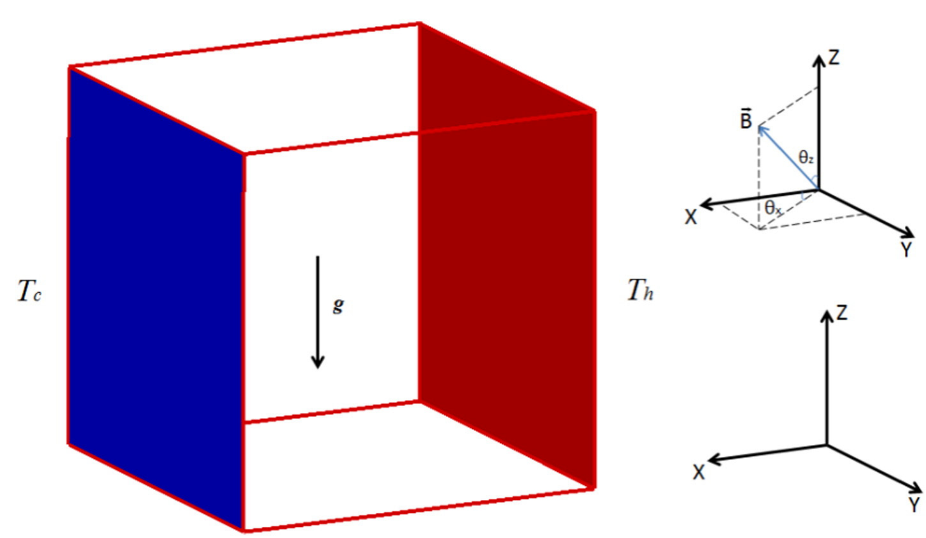

Fig. 1. Schematic domain of the physical model.