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Study on the flow and heat transfer of liquid metal based nanofluid with different nanoparticle radiuses using two-phase lattice Boltzmann method

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ABSTRACT

A two-phase lattice Boltzmann model considering the interaction forces of nanofluid has been developed in this paper. It is applied to investigate the flow and natural convection heat transfer of Cu–Ga nanofluid. The effects of different nanoparticle radiuses, interaction forces, aspect ratios of the enclosure, nanoparticle volume fractions, and Rayleigh numbers on the nanoparticle distributions and heat transfer characteristics are investigated. It is found that the nanofluid with small nanoparticle radius significantly improves the heat transfer compared with the nanofluid with big nanoparticle radius. The temperature difference driving force has the biggest effect on the nanoparticle distribution, followed by the Brownian force and drag force, and the other forces have the least effect. The average Nusselt number increases with the increasing aspect ratio of the enclosure, nanoparticle volume fraction and Rayleigh number.

1. Introduction

Due to the shortage of energy, the high-efficiency and compact heat exchanger is necessary. The traditional heat transfer mediums (water, ethylene glycol, oil and so on.) cannot meet the high intensity of heat transfer in many fields, for example, the cooling of high temperature superconductor, the thermal management of high power electronic component, the thermal control of spacecraft, the strengthening heat transfer of heat exchanger and the heat dissipation of computer component. Based on these applications of heat transfer, the concept of nanofluid is brought forward. Since nanofluid is prepared by adding nanoparticles into base fluid, nanofluid is applied in more and more fields (for example, cooling of microchannel heat sink [1,2]) due to its high thermal conductivity coefficient. People have widely investigated the thermal conductivity [3,4], viscosity [5], unsteady characteristics [6,7].

Flow and natural convection heat transfer of nanofluid are studied by various methods. In addition to experimental methods [8,9], in order to save time and cost, numerical simulation is an important method for nanofluid. Researchers used various traditional numerical simulation methods to investigate the nanofluid:two-phase mixture model [10], Eulerian–Lagrangian approach [11], two-phase model solved by homotopy perturbation method [12], differential transformation method [13] and least square method [14]. In addition to these traditional methods, a new method, lattice Boltzmann method, is applied widely in the nanofluid recently [15]. Sheikholeslami et al. [16–18] investigated the natural convection heat transfer of Al_2O_3–water and Cu–water nanofluid by lattice Boltzmann model and control volume based finite element method respectively. In addition, the magnetic field effects on natural convection heat transfer and forced convection heat transfer of different kinds of nanofluid and ferrofluid are widely investigated by Sheikholeslami et al. [19–24]. Groşan et al. [25] investigated the natural convection heat transfer of nanofluid in a square enclosure filled with a saturated porous medium. Nanofluid is a two-phase fluid, and the Brownian motion and thermophoresis between particles have important effects on the flow and heat transfer of nanofluid. Sheikholeslami et al. [26,13,27–30] investigated the effects of Brownian motion and thermophoresis on the heat transfer of nanofluid.

Above experimental and numerical studies on natural convection heat transfer mainly focus on the effects of aspect ratio of enclosure, nanoparticle volume fraction and Rayleigh number on the flow and natural convection heat transfer. In addition to the common factors (aspect ratio of enclosure, nanoparticle volume fraction and Rayleigh number), the interaction forces and nanoparticle radius are also very important for the flow and natural convection heat transfer of nanofluid. However, the investigations

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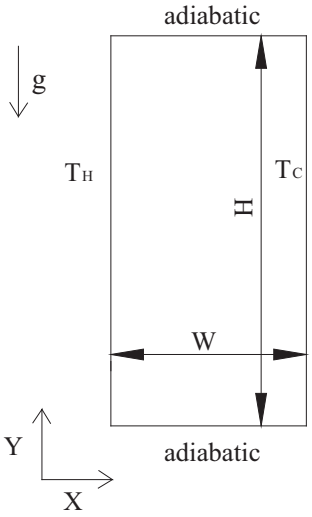

Fig. 1. Rectangular enclosure.

on the details of different interaction forces, the nanoparticle distribution, and the effects of different nanoparticle radii on flow and natural convection heat transfer are rare. Due to low thermal conductivity coefficient of traditional base fluid, which cannot meet the high intensity of heat transfer in many fields, a higher thermal conductivity coefficient base fluid–liquid Ga is chosen as the base fluid in this paper, and Cu is chosen as the nanoparticles. A two-phase lattice Boltzmann model considering the interaction forces is developed in this paper, and it is applied to investigate the natural convection heat transfer of the rectangular enclosure filled with Cu–Ga nanofluid with different nanoparticle sizes. The novelty of this paper mainly includes: The distribution of interaction forces in enclosure and the range of every interaction force are investigated, and the effects of interaction forces on flow and natural convection heat transfer are analyzed in this paper. The heat transfer enhancement mechanism of nanofluid is revealed in this paper. Liquid metal Ga is chosen as the base fluid, and the effects of different nanoparticle radius on flow and natural convection heat transfer are investigated in this paper, which provides a theoretical basis for the selection of nanoparticle size.

2. Method

2.1. Two-phase lattice Boltzmann model

Single-phase model ignores the drag force and other interaction forces, which causes some errors in the results. However, two-phase model considering interaction forces can prevent the errors of single-phase model. In addition, unlike single-phase model, two-phase model not only can be used to investigate the effects of interaction forces and nanoparticle radius on the heat transfer of nanofluid, but also the nanoparticle distribution. A two-phase lattice Boltzmann model is established in this paper by coupling the velocity evolution equation and temperature evolution equation.

Table 1
Thermo-physical parameters of liquid metal gallium and copper nanoparticle [33].

Physical properties	Base fluid (Ga)	Nanoparticle (Cu)
ρ (kg/m^3)	6090	8978
c_p (J/kg k)	429.9–0.275543T	381
μ (m^2/s)	0.0018879	/
k (W m^{-1} K^{-1})	31	387.6

Table 2
Numerical simulation results at different grids ($Ra = 1 \times 10^5$, $\varphi = 0.05$).

Grid number	39×78	64×128	99×198	128×256	150×300
Nu_{avg}	1.583	1.770	1.799	1.805	1.806

D2Q9 model is adopted in the velocity evolution equation, and the detail of the evolution equation is shown as follows:

$$f_\alpha^\sigma(\boldsymbol{r}+\boldsymbol{e}_\alpha\delta_t, t+\delta_t) - f_\alpha^\sigma(\boldsymbol{r},t) = -\frac{1}{\tau_f^\sigma}\left[f_\alpha^\sigma(\boldsymbol{r},t) - f_\alpha^{\sigma eq}(\boldsymbol{r},t)\right] + \frac{2\tau_f^\sigma - 1}{2\tau_f^\sigma}\cdot\frac{F_\alpha^\sigma \delta_t \boldsymbol{e}_\alpha}{B_\alpha c^2} + \delta_t F_\alpha^{\sigma'} \quad (1)$$

where τ_f^σ is the dimensionless collision–relaxation time for the flow field, $\boldsymbol{e}_\alpha$ is the lattice velocity vector, the subscript α represents the lattice velocity direction, σ is the component ($\sigma = 1, 2$ represent base fluid and nanoparticle respectively), $f_\alpha^\sigma(\boldsymbol{r},t)$ is the distribution function of the nanofluid with velocity $\boldsymbol{e}_\alpha$ (along the direction α) at lattice $\boldsymbol{r}$ and time t, $f_\alpha^{\sigma eq}(\boldsymbol{r},t)$ is the local equilibrium distribution function, δ_t is the time step t, F_α^σ is the total inter-particle interaction forces, B_α is one of the weight coefficients, $c = \delta_x/\delta_t$ is the reference lattice velocity, δ_x is the lattice step, the order numbers $\alpha = 1, \ldots, 4$ and $\alpha = 5, \ldots, 8$ represent the rectangular directions and the diagonal directions of a lattice respectively, F_α^σ is the total inter-particle interaction forces, $F_\alpha^{\sigma'} = \boldsymbol{G}\cdot\frac{(\boldsymbol{e}_\alpha - \boldsymbol{u}^\sigma)}{p} f_\alpha^{\sigma eq}$ is the external force term in the direction of lattice velocity without inter-particle interaction, $\boldsymbol{G} = -\beta(T_{nf} - T_0)\boldsymbol{g}$ is the effective external force, where $\boldsymbol{g}$ is the gravity acceleration, β is the thermal expansion coefficient, T_{nf} is the temperature of nanofluid, T_0 is the mean value of the high temperature and low temperature of the walls.

The weight coefficient B_α is given as:

$$B_\alpha = 0 \ \ (\alpha = 0), \quad B_\alpha = 1/3 \ \ (\alpha = 1, \ldots, 4), \quad B_\alpha = 1/12 \ \ (\alpha = 5, \ldots, 8) \quad (2)$$

D2Q9 model is adopted in the velocity evolution equation, and the discrete velocity set for each component α is:

$$\boldsymbol{e}_\alpha = \begin{cases} (0,0) & \alpha = 0 \\ c\left(\cos\left[(\alpha-1)\frac{\pi}{2}\right], \sin\left[(\alpha-1)\frac{\pi}{2}\right]\right) & \alpha = 1,2,3,4 \\ \sqrt{2}c\left(\cos\left[(2\alpha-1)\frac{\pi}{4}\right], \sin\left[(2\alpha-1)\frac{\pi}{4}\right]\right) & \alpha = 5,6,7,8 \end{cases} \quad (3)$$

The velocity equilibrium distribution function is shown as follows:

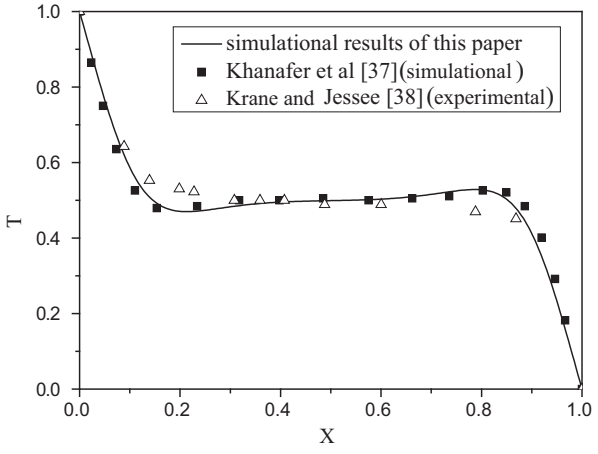

Fig. 2. Temperature distributions in the horizontal mid-line.