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Recent progress on lattice Boltzmann simulation of nanofluids: A review☆

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ABSTRACT

Researches on nanofluids have been quite intensive in the past decade. The performances of nanofluids have been experimentally and theoretically investigated by various researchers across the world. Among the proposed numerical methods, the lattice Boltzmann method has been shown to predict the heat transfer augmentation by nanofluids at acceptable accuracy. In this review, we summarize the recent progress of lattice Boltzmann formulation in predicting nanofluids and try to find some challenging issues that need to be solved for future research.

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1. Introduction

Over the years, convective heat transfer has been a challenge and an interesting problem to researchers. The subject is not only important in real engineering applications such as the cooling of electronics components, nuclear reactor, building heating and cooling, etc. but also in daily life experiences for example double pane insulation panels, water boiling and ventilation system. Convective heat transfer by nanofluid is also one of the current focuses in computational fluid dynamics field in which the percentage of nanoparticles and the types of nanoparticles (thermal conductivity) are the important parameters. The application of nanoparticle is one of the new techniques in many practical heat and fluid flow situations (e.g. heat exchanger, solar energy collector, chemical vapour deposition instrument, etc.). It is also known that nanofluids offer better mixing of flow and higher heat transfer rate than the pure fluid. Since the first introduction of nanofluids, many researchers have devoted their focus to investigate the applicability of this new generation of heat transfer fluid in real engineering applications [1–9].

Till the present day, most researchers rely on computational rather than experimental approach to study the augmented heat transfer by nanofluids. Indeed Xuan and Li [10], Yang et al. [11] and Chon et al. [12] reported detail experimental results on the convective heat transfer and flow features of nanofluids. However, according to these papers, high accuracy of research equipment together with data interpretation system is required to obtain reliable experimental data. Such these high cost experimental devices will not be affordable if not supported by research fund.

As an alternative approach, many researchers considered fully computational scheme in their investigations [13–19]. With the advanced of computing technology, the performance of various types of nanofluids at wider range of flow parameters can be analysed. As computational model predicts excellent results when compared to the experimental results, however, the complicated nature of Navier–Stokes equation demands high computational time in resolving fluid part. In contrast, the mathematical foundation of lattice Boltzmann method (LBM) [20–23] makes it a suitable numerical tool for heat–fluid prediction.

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LBM foundation adopts the kinetic theory of gases which considers the evolution of fluid based on the behaviour at molecular level. Accordingly, LBM resolves the macroscale of fluid flow indirectly by solving the evolution equation of particle distribution function and models the propagation and collision of particle distribution which are believed to be the fundamental behaviours at molecular level. While the previous researches have demonstrated the vast application of LBM in predicting heat and fluid problem, however, literature records indicate that the use of LBM to investigate the augmentation of heat transfer by nanofluids is still at its infancy. Therefore, this paper aims to provide comprehensive review focuses on the fundamental and applied research on the LBM specifically on the convective heat transfer by nanofluids. The progress of the available research will be summarized and research challenges and future research needs will be identified in this review.

2. Double distribution function lattice Boltzmann method

Unlike other numerical methods, LBM predicts the evolution of particle distribution function and calculates the macroscopic variables by taking moment to the distribution function [24–29]. LBM starts with the Boltzmann equation, discretised in space and time, given as:

$$f_i(\mathbf{x}+\mathbf{e}_i, t+1)-f_i(\mathbf{x},t)=\frac{1}{\tau_f}\left[f_i(\mathbf{x},t)-f_i^{eq}(\mathbf{x},t)\right]+F \tag{1}$$

$$g_i(\mathbf{x}+\mathbf{e}_i, t+1)-g_i(\mathbf{x},t)=\frac{1}{\tau_g}\left[g_i(\mathbf{x},t)-g_i^{eq}(\mathbf{x},t)\right] \tag{2}$$

where distribution function f is used to calculate density and velocity fields and distribution function g is used to calculate temperature field. F is the external force and τ_f and τ_g are the relaxation times carried by the momentum and energy respectively.

The equilibrium distribution functions f_i^{eq} and g_i^{eq} are chosen so that they satisfy the macroscopic equations via Chapman–Enskog expansion. They can be written as [30–32]:

$$f_i^{eq}=\rho\omega_i\left[1+3\frac{\mathbf{e}_i\cdot\mathbf{u}}{c^2}+9\frac{(\mathbf{e}_i\cdot\mathbf{u})^2}{2c^4}-\frac{3\mathbf{u}^2}{2c^2}\right] \tag{3}$$

$$g_i^{eq}=\rho T\omega_i\left[1+3\frac{\mathbf{e}_i\cdot\mathbf{u}}{c^2}+9\frac{(\mathbf{e}_i\cdot\mathbf{u})^2}{2c^4}-\frac{3\mathbf{u}^2}{2c^2}\right]. \tag{4}$$

The values of the weight ω_i depend on the chosen lattice model.

The macroscopic variables such as density, velocity and temperature can be calculated by taking moment to the distribution functions as follow [33–35]:

$$\sum_i f_i^{eq}=\rho,\quad \sum_i e_{i,\alpha}f_i^{eq}=\rho u_\alpha,\quad \sum_i e_{i,\alpha}f_i^{eq}=\rho T. \tag{5}$$

3. Convective heat transfer of nanofluids

Prediction of nanofluid flow characteristics using lattice Boltzmann method was initiated by Xuan and his co-workers in 2003 [36–42]. According to Xuan and Yao [38], the total forces acting on the nanoparticles in nanofluid can be described based on the colloid theory [43] as follows:

$$F_P=n(F_H+F_D+F_A+F_B)/V \tag{6}$$

where the interaction potential force, F_A

$$F_A=\sum_{i=1}^{8}n_i\frac{\partial V_A}{\partial r_i} \tag{7}$$

the Brownian force, F_B

$$F_B=G_i\sqrt{\frac{c}{dt}} \tag{8}$$

the Stokes force (drag force), F_D

$$F_D=-6\pi\mu\alpha\Delta u \tag{9}$$

and the gravity and buoyancy forces, F_H

$$F_H=-\frac{4\pi\alpha^3}{3}g\Delta\rho'. \tag{10}$$

On the other hand, the forces on the fluid particles can be expressed as reaction of drag and Brownian forces.

Xuan and Yao [38] concluded that the strength of Brownian force is the dominant factor for the agglomeration or random displacement of nanoparticles. However, there were some limitations on the model such that there is no possibility to include thermal parameters such as thermal conductivity and thermal diffusivity.

Few years later, Nemati et al. [44] predicted the mixed convection of three nanofluids in lid-driven cavity at Re = 1, 10 and 100 and Rayleigh number 10^4. The nanofluid parameters have been recalculated based on the fraction of nanoparticles as follows:

The effect of density at the reference temperature:

$$\rho_{nf}=(1-\phi)\rho_f+\phi\rho_s. \tag{11}$$

The heat capacitance and thermal expansion of nanofluid

$$(\rho c_p)_{nf}=(1-\phi)(\rho c_p)_f+\phi(\rho c_p)_s \tag{12}$$

$$(\rho\beta)_{nf}=(1-\phi)(\rho\beta)_f+\phi(\rho\beta)_s. \tag{13}$$

The viscosity of the nanofluid containing a dilute suspension of small rigid spherical particles is given by Brinkman model [45–50] as:

$$\mu_{nf}=\frac{\mu_f}{(1-\phi)^{2.5}}. \tag{14}$$

The effective thermal conductivity of the two component entities of spherical-particle suspension was introduced by Chon et al. [51] as follows:

$$\frac{k_{nf}}{k_f}=1+64.7\phi^{0.764}\left(\frac{d_f}{d_s}\right)^{0.369}\left(\frac{k_f}{k}\right)^{0.7476}Pr_T Re_T^{1.2321}. \tag{15}$$

They found that the type of nanofluid is a key factor for heat transfer enhancement and the highest and lowest values of Nu number are obtained when using Cu and Al_2O_3 nanoparticles respectively.

Other than the formulation of viscosity and thermal conductivity as in Eqs. (14)–(15), many other researchers consider the following equations for viscosity and thermal conductivity (Tables 1 and 2).

Predictions of convective heat transfer by nanofluids using the lattice Boltzmann method over different kinds of geometries have also attracted many researchers. He et al. [78], Kefayati et al. [79], Lai and Yang [80] and many more [81–88] dedicated their study on the nanofluid flow and heat transfer characteristics inside a conventional differentially heat side walls of rectangular enclosure. On the other hand, Sajjadi et al. [89], Hosseini et al. [90] and Karimipour et al. [91] extended the research on the effect of inclination angles on the heat transfer efficiency inside the enclosure. Sheikholeslami and Ganji [92], Sheikholeslami et al. [93–97], Darzi et al. [98], Ashorynejad [99] and Mehrizi et al. [100] focused on the heat transfer and vortex structure