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Effects of temperature-dependent properties on natural convection of power-law nanofluids in rectangular cavities with sinusoidal temperature distribution

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ABSTRACT

In this paper, the effects of temperature-dependent properties on natural convection of nanofluids in rectangular cavities with sinusoidal temperature distribution are investigated in detail with lattice Boltzmann method. To improve the computational efficiency, all simulations are performed on the Graphics Processing Unit (GPU) using NVIDIA's CUDA. The fluid in the enclosure is a water-based nanofluid containing Al_2O_3 nanoparticles. The effects of power-law index ($0.5 \leqslant n \leqslant 1.5$), thermal Rayleigh number ($10^4 \leqslant Ra_f \leqslant 10^6$), diameter of nanoparticle ($25\,\text{nm} \leqslant d_s \leqslant 100\,\text{nm}$), nanoparticle volume fraction ($0.0 \leqslant \phi \leqslant 0.04$), temperature of the cooled sidewall ($315\,\text{K} \leqslant T_c \leqslant 335\,\text{K}$), temperature difference between the sidewalls ($10\,\text{K} \leqslant \Delta T \leqslant 50\,\text{K}$), amplitude ratio ($0.0 \leqslant A \leqslant 1.0$), wave number ($0.0 \leqslant \omega \leqslant 6.0$), phase deviation ($0.0 \leqslant \theta \leqslant \pi$) and aspect ratio ($0.250 \leqslant AR \leqslant 4.00$) on heat and fluid flows are investigated. The results reveal that there is an optimal volume fraction ϕ_{opt} at which the maximum heat transfer enhancement is obtained, and the value of ϕ_{opt} is found to increase slightly with decreasing the nanoparticle diameter, and to increase remarkably with increasing the temperature of T_c or ΔT. In addition, the average Nusselt number is generally decreased with increasing power-law index, while increased with increasing A and ω. Further, we found that the average Nusselt number behaves nonlinearly with the phase deviation parameter. Moreover, the present results also indicate that there is an optimal value of aspect ratio at which the impact of AR on heat transfer is the most pronounced.

1. Introduction

During the past decades, natural convection in enclosures has draw considerable attention due to its importance and wide applications in various fields, such as heat exchangers, cooling of electronic systems and furnace engineering [1–3]. Enhancing the heat transfer efficiency in these systems is usually an essential topic from an energy saving perspective. However, conventional heat transfer fluids like water, ethylene glycol and engine oil have relative low thermal conductivity values, thus limit the heat transfer rate. Fortunately, due to recent progress in nanotechnology, thermal conductivity values can be increased by dispersing nanometer-sized particles in conventional heat transfer fluids to form the so-called nanofluids [4], and this also explains why nanofluids have found such a wide applications in some engineering applications [5].

Over the last few decades, a great number of numerical efforts have been made to investigate the basic mechanism of the enhanced heat transfer characteristics in nanofluids. For instance, Khanafar et al. [6] numerically investigated the buoyancy driven heat transfer enhancement in a two-dimensional enclosure utilizing Cu-water nanofluid. It was observed that the heat transfer rate across the enclosure is increased with the increase of nanoparticle volume fraction for any Grashof numbers. Jahanshahi et al. [7] studied the influence of uncertainties due to adopting various formulae for the effective thermal conductivity of SiO_2-water on heat transfer characteristics for natural convection in a square enclosure. And the results reveal that heat transfer rate is increased with the addition of nanoparticle volume fraction when employing experimental thermal conductivity, whereas it is decreased as using theoretical thermal conductivity. More recently, Xu et al.

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[8] numerically investigated the natural convection of nanofluids in a metal-foam cavity, and they found that the Nusselt number of the natural convection increases in the Darcy number and the effective thermal conductivity. Kefayati [9] examined the heat transfer and entropy generation for laminar natural convection of non-Newtonian nanofluids in a square cavity, and the results indicate that an increase in Darcy number causes the heat transfer rate and entropy generation decrease considerably. Additionally, the author also performed some simulations to investigate the magnetic field effects for the same configuration [10]. For more numerical studies on natural convection in enclosures, we refer the reader to the review presented by Abouali et al. [11].

The aforementioned investigations show that the thermally active walls of the enclosure considered in most previous works are uniformly heated. However, convection heat transfer in cavities with nonuniform temperature distributions is frequently encountered in many engineering problems [12]. In view of these aspects, recently some studies on natural convection in enclosures with different temperature conditions have been conducted by some researchers. Cheong et al. [13] did research on the effects of aspect ratio on natural convection in an inclined rectangular enclosure with sinusoidal temperature distributions on the vertical left wall. Kefayati [14] numerically investigated the effect of a magnetic field on natural convection of nanofluid with sinusoidal temperature distribution on the right sidewall, and it was demonstrated that the variations of the Hartmann number and the phase deviation have a great influence on the heat transfer rate. In addition, natural convection of nanofluid in porous cavities with sinusoidal thermal conditions on both sidewalls was investigated by Sheremet and Pop [15,16]. Quite recently, Alsabery et al. [17] analyzed the natural convective heat transfer of non-Newtonian nanofluid in a trapezoidal cavity with sinusoidal boundary conditions on both side walls, and the authors also examined the natural convection of nanofluid in an inclined square enclosure partially filled with a porous medium [18]. Pordanjani [19] studied the effect of two isothermal obstacles on the natural convection of nanofluid in the presence of magnetic field inside an enclosure with sinusoidal wall temperature distribution.

Although there was a great deal of studies on natural convection using nanofluid, there are still some fundamental issues needed to be investigated. First, it is worth noticing that in most previous works the effective thermal conductivity is calculated by employing the classical Maxwell-Garnett model [20], and it has been demonstrated that this model behaves well when the nanofluid is at ambient temperature, but it tends to fail dramatically as the nanofluid temperature is one or some tens degrees higher than “room” temperature [21]. Additionally, the commonly used Brinkman equation is found to underestimate the dynamic viscosity of the nanofluid, particularly for the smaller nanoparticle diameter [22,23]. To some extent, the deficiencies of such classical models can be attributed to the fact that they include only the effect of the nanoparticle volume fraction. In this context, more detailed works that take into account the effects of other physical properties, such as temperature and nanoparticle diameter, are needed to investigate the heat transfer and fluid flow of nanofluids. Further, a careful review of the literature reveals that the base fluid used in existing works was usually considered to be Newtonian, the case of non-Newtonian nanofluid has received less attention (if any, the thermally active walls considered are always uniformly heated [9] and/or the physical properties of nanofluids are usually assumed to be independent of temperature [17]). In fact, to the best knowledge of authors, there are no studies reported in the literature to investigate the effects of temperature-dependent properties on natural convection of non-Newtonian nanofluid in rectangular enclosure with sinusoidal temperature distribution.

Framed in this general background, the aim of the present paper is to systematically investigate the effects of temperature-dependent properties on natural convection of non-Newtonian nanofluid in rectangular enclosure with sinusoidal temperature distribution. Additionally, the effective thermal conductivity and dynamic viscosity of the nanofluid are calculated by employing Corcione’s correlations [23], which are agree sufficiently well with a high number of experimental data available in the literature. Further, as far as the numerical method is concerned, here we consider the lattice Boltzmann (LB) method, which has gain a great success in the study of complex problems across a broad range of scales [24–32], as well as nanofluid flows [8,33–35]. Compared with the traditional computational fluid dynamics methods based on the macroscopic continuum equations, the LB method has some distinct advantages, such as easy implementation of boundary conditions and fully parallel algorithms. For this reason, in this paper, the LB method is implemented on the Graphic Processing Unit (GPU) using NVIDIA’s CUDA for a high calculating speed.

The layout of the paper is as follows. In the following section, we briefly review the physical properties of nanofluids, and present the configuration and governing equations of the physical problem considered in this work. In Section 3, the LB model for natural convection of nanofluid is introduced. In Section 4, we validated the numerical method by considering two tests. The numerical results and discussion are present in Section 5. Finally, some conclusions are given in Section 6.

2. Mathematical formulation

2.1. Physical properties of nanofluids

In this paper, the single-phase approach for nanofluid modeling is adopted [36]. In this approach, it is assumed that both the fluid phase and nanoparticles are in the thermal equilibrium state, and the influence of addition of nanoparticles into base fluid are reflected by changing thermophysical properties of the mixture. In such a case, the properties of the nanofluid are usually calculated as functions of nanoparticle properties, base fluid properties and nanoparticle volume fraction. The thermophysical properties of water and Al_2O_3 considered here are shown in Table 1.

In addition, it should be noted that the numerical results for the single-phase approach depend strongly on the selected thermophysical property models, especially those for the thermal conductivity and dynamic viscosity [37]. In the present work, the Corcione’s correlations [23] are employed to predicted the effective thermal conductivity k_{nf} and the viscosity μ_{nf} of the nanofluids, which have shown good agreement with the experimental data [23,38], and the corresponding equations read

$$k_{nf} = k_f\left[1 + 4.4Re^{0.4}Pr^{0.66}\left(\frac{T}{T_{fr}}\right)^{10}\left(\frac{k_s}{k_f}\right)^{0.03}\phi^{0.66}\right], \tag{1}$$

$$\mu_{nf} = \frac{\mu_f}{1 - 34.87\left(\frac{d_p}{d_f}\right)^{-0.3}\phi^{1.03}}, \tag{2}$$

in which ϕ refers to the volume fraction of nanoparticles, and the subscripts nf, f, s denote the nanofluid, base fluid and nanoparticle, respectively. Pr is the Prandtl number of the base fluid (i.e., water), T is the nanofluid temperature, T_{fr} is the freezing point of the base fluid, d_p is diameter of the nanoparticle, d_f is the equivalent diameter of the base fluid molecule, and can be given by

$$d_f = 0.1\left(\frac{6M}{\mathrm{N}\mathrm{A}\pi\rho_{f0}}\right)^{1/3}, \tag{3}$$