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Heat transfer and entropy generation of natural convection on non-Newtonian nanofluids in a porous cavity

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ABSTRACT

In this paper, heat transfer and entropy generation on laminar natural convection of non-Newtonian nanofluids in a porous square cavity have been analyzed by Finite Difference Lattice Boltzmann Method (FDLBM). The porous cavity is filled with water and nanoparticles of copper (Cu) while the mixture shows shear-thinning behavior. This study has been conducted for the certain pertinent parameters of Rayleigh number ($Ra = 10^4$–10^5), Darcy number ($Da = 0.001$, 0.01, and 0.1), and power-law index ($n = 0.6$–1), and the volume fraction has been studied from $\varphi = 0$ to 0.04. Results indicate that heat transfer and different irreversibilities enhance as Rayleigh number increases. The enhancement of the volume fraction augments heat transfer and the entropy generations due to heat transfer and fluid friction. The drop of the Darcy number causes the heat transfer and different entropy generations to decline considerably. Interestingly, the behavior of heat transfer and the studied entropy generations against the alteration of the power-law index is different in various Darcy numbers. In addition, the Bejan number demonstrates that the proportion of the irreversibilities due to heat transfer and fluid friction changes with the variation of the scrutinized parameters.

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1. Introduction

1.1. Background

The fluids that are traditionally used for heat transfer applications such as water, mineral oils and ethylene glycol have a rather low thermal conductivity and they cannot play as an efficient heat transfer agent. Nanoparticles are known as an efficient way for improvement of thermal conductivity of base fluids. Fluids with nanoparticles suspended in them are called nanofluids. Nanofluids have anomalous high thermal conductivity at very low nanoparticles concentration and considerable enhancement of forced convective heat transfer. As a result, nanofluid has received high attention in heat transfer area. Flow in an enclosure driven by buoyancy force is a fundamental problem in fluid mechanics and heat transfer. This type of flow can be utilized as a validation in academic researches and various applications of engineering. Hence, several studies into natural convection of nanofluid have been conducted analytically, numerically and experimentally by different researchers [1–18]. On the other hand, the utilized cavity could be replaced simply with a porous cavity in some industries such as geothermal reservoirs, catalytic reactors, spreading of pollutants, solar collectors and interestingly, nanofluid is playing a crucial role in cooling and heating systems in the cited industries. As a result, several investigations have been conducted into the natural convection of nanofluid in porous enclosures recently. Sheremet and Pop [19] scrutinized steady-state natural convection heat transfer in a square porous enclosure having solid walls of finite thickness and conductivity filled by a nanofluid using the mathematical nanofluid model proposed by Buongiorno. Bourantas et al. [20] studied natural convection of a nanofluid in a square cavity filled with a porous matrix numerically using a meshless technique. The effect of the porous medium in the cooling efficiency of the nanofluidic system was discussed. Sheremet et al. [21] simulated transient natural convection in a porous wavy-walled cavity filled with a nanofluid. The main objective is to investigate the effects of the dimensionless time, thermal dispersion parameter and solid volume fraction parameters of nanoparticles on the fluid flow and heat transfer characteristics.

For the all of the mentioned numerical investigations, the base fluid was assumed to be Newtonian, but it is demonstrated that many nanofluids exhibit non-Newtonian, mainly shear-thinning behavior [22–29]. Therefore, it is necessary to be considered the effect of shear-thinning behavior of nanofluids. Moreover, the optimal design of heat transfer process in different industries is obtained with precision calculation of entropy generation since it clarifies energy losses in a system evidently. Hence, entropy generation is investigated into natural convection of pure fluids [30,31] and nanofluids in multifarious shapes extensively. Shahi et al. [32] studied the entropy generation induced by natural convection heat transfer in a square cavity containing Cu–

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water nanofluid and a protruding heat source. It was found that the Nusselt number increased and the entropy generation reduced as the nanoparticle volume fraction was augmented. In addition, it was shown that the heat transfer performance could be maximized and the entropy generation minimized by positioning the heat source on the lower cavity wall. Esmaeilpour and Abdollahzadeh [33] examined the natural convection heat transfer behavior and entropy generation rate in a Cu–water nanofluid-filled cavity comprising two vertical wavy surfaces with different temperatures and two horizontal flat surfaces with thermal insulation. The results showed that the mean Nusselt number and entropy generation rate both decreased as the volume fractions of nanoparticles increased. It was also shown that the mean Nusselt number and rate of entropy generation increased with the rise of Grashof number, but decreased with the enhancement of the surface amplitude. Cho et al. [34] investigated the natural convection heat transfer performance and entropy generation rate in a water based nanofluid-filled cavity bounded by a left wavy-wall with a constant heat flux, a right wavy-wall with a constant low temperature, and flat upper and lower walls with adiabatic conditions. The results showed that the mean Nusselt number increased and the entropy generation rate decreased as the volume fraction of nanoparticles increased. Cho [35] performed a numerical simulation into heat transfer and entropy generation of natural convection in a partially-heated wavy-wall square cavity filled with Al_2O_3–water nanofluid. In the study, it was mentioned that the mean Nusselt number increases and the total entropy generation decreases as the volume fraction of Al_2O_3 nanoparticles increases. Sheikholeslami et al. [36] investigated nanofluid flow and heat transfer in a square enclosure containing a rectangular heated body computationally. The results indicated that both the Nusselt number and dimensionless entropy generation enhances when the Rayleigh number and nanoparticle volume fraction rise. Kefayati [37] analyzed heat transfer and entropy generation due to laminar natural convection in a square cavity filled with non-Newtonian nanofluid. It was found that entropy generation due to fluid friction and heat transfer rise as the Rayleigh number enhances. In addition, augmentation of volume fraction enhances entropy generations due to heat transfer and fluid friction in different power-law indexes.

Lattice Boltzmann method has been a powerful mesoscopic method in different subjects and shapes such as nanofluid, ferrofluid, MHD flow, porous medium, turbulent flow, melting and so on [38–50]. However, it does not have the considerable success in non-Newtonian fluid especially for non-isothermal problems. Hence, the simulation of the problem requires a special innovative numerical method which has the capacity to solve the problem accurately and efficiently while protects the merit of LBM. Therefore, Finite Difference Lattice Boltzmann Method (FDLBM) has been applied to solve the problem as it has the ability to derive the shear stresses equations in the form of the classical equations in contrast with Lattice Boltzmann Method (LBM). Independency of the method to the relaxation time in contrast with the common LBM causes the method to solve different non-Newtonian fluid energy equations successfully as the method protects the positive points of LBM simultaneously. In addition, the validation of the method and its mesh independency demonstrates that is more capable than conventional LBM. The method has been proposed by Fu et al. [51]. Moreover, Kefayati [52–70] developed and applied the FDLBM to simulate various complicated problems recently.

The main aim of this study is to simulate laminar natural convection of non-Newtonian nanofluid in a porous square cavity by FDLBM. It is endeavored to express the effect of different parameters on the flow and thermal fields. In addition, the energy management of the problem is analyzed by studying the entropy generations due to heat transfer and fluid friction as the proportions of the irreversibilities are investigated by the average Bejan number. The results of FDLBM are validated with previous numerical investigations and the effects of the main parameters (power-law index, volume fraction, Darcy number and Rayleigh number) on the flow and energy fields as well as the entropy generation are researched.

2. Problem statement

The geometry of the present problem is shown in Fig. 1. It consists of a two-dimensional cavity with the height of L. The temperature of the left wall has been considered to be maintained at high temperature of T_H as the right sidewall is kept at low temperature of T_C. The horizontal walls are adiabatic and impermeable. The porous cavity is filled with a non-Newtonian shear-thinning nanofluid of water/Cu where the pertinent thermophysical properties are given in Table 1. The general form of the momentum equation of incompressible fluid in saturated variable porosity can be derived by averaging the Navier–Stokes equations over the representative elementary volume (REV). The Brinkman-extended Darcy model without the inertia term is applied for the simulation of the porous media as it has been used in a large number of investigations for natural convection in rectangular porous enclosures [69–73]. Uniform porosity and permeability has been applied in this study. The ratios of the thermophysical properties of the porous medium and of the fluid, for the specific heat $\sigma = \frac{(\rho c_p)_m}{(\rho c_p)_f}$, for the thermal conductivity $R_k = \frac{k_m}{k_f}$, and for viscosity $\Lambda = \frac{\mu_m}{\mu_f}$are equal to one. The flow is incompressible, steady, and laminar. It is assumed that nanoparticles are suspended in the nanofluid using either surfactant or surface charge technology. Further, it is assumed that the liquid and solid are in thermal equilibrium and they flow at the same velocity. The density variation is approximated by the standard Boussinesq model. In addition, the viscous dissipation in the energy equation has been neglected.

3. Theoretical formulation

3.1. Dimensional equations

Considering the above assumptions, the following governing equations are used to represent the flow phenomena [37,69].

$$\frac{\partial \overline{u}}{\partial \overline{x}} + \frac{\partial \overline{v}}{\partial \overline{y}} = 0 \tag{1}$$

$$\rho_{nf}\left(\frac{\partial \overline{u}}{\partial \overline{t}} + \overline{u}\frac{\partial \overline{u}}{\partial \overline{x}} + \overline{v}\frac{\partial \overline{u}}{\partial \overline{y}}\right) = -\frac{\partial \overline{P}}{\partial \overline{x}} + \left(\frac{\partial \overline{\tau}_{xx}}{\partial \overline{x}} + \frac{\partial \overline{\tau}_{xy}}{\partial \overline{y}}\right) - \frac{\overline{\mu}_{nf}}{K}\overline{u} \tag{2}$$

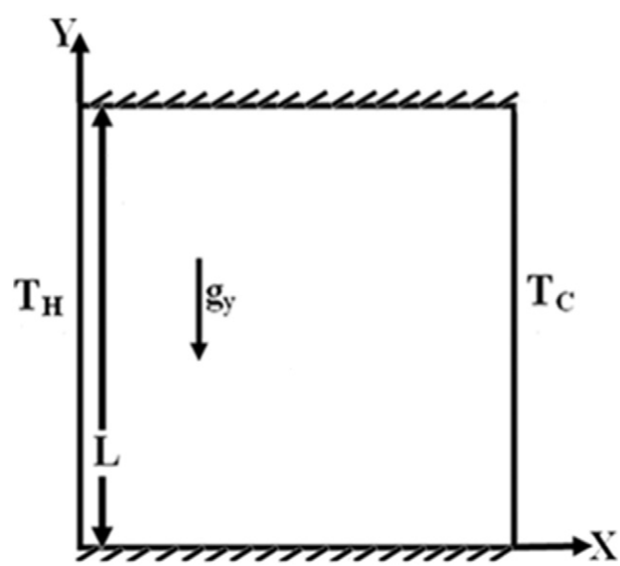

Fig. 1. Geometry of the present study.

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