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Free convection in a square cavity filled by a porous medium saturated by a nanofluid: Viscous dissipation and radiation effects

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ABSTRACT

The influence of the viscous dissipation and radiation effects on the natural convection heat transfer in a square cavity filled with porous media saturated with a nanofluid is studied. The vertical walls of the cavity are subject to finite temperature difference while the top and bottom walls of the cavity are insulated. The Buongiorno's nanofluid model, incorporating the Brownian motion and thermophoresis effects, is employed. The governing equations, in nondimensional form, are written in the weak form and solved using the finite element method. The influences of viscous dissipation and radiation effects on the concentration distribution of nanoparticles are discussed. The average and local Nusselt numbers are reported for various values of viscous dissipation (Eckert number) and radiation effects. The results show that the Nusselt numbers at the hot and cold walls are not equal due to the presence of viscous dissipation effects. The raise of Eckert number decreases the Nusselt number at hot wall, but it increases the Nusselt number at the cold wall. It is also found that the increase of Lewis number enhances the heat transfer in the cavity.

1. Introduction

The heat transfer of nanofluids in porous media has gained considerable attention and many valuable studies have been performed in this subject. Consideration of the heat released by viscous dissipation depends on the other thermal sources, influencing the heat transfer in the fluid motion such as localized heat sources or sinks or buoyancy forces induced by heated or cooled walls. The heat released by viscous dissipation in natural convection could be significant in various devices, subject to large decelerations or which operate at high rotational speeds or stronger gravitational fields and in processes wherein the scale of the process is very large [1]. The flat plate solar collectors, supported with metallic porous foams indeed are cavities subject to internal heat generation due to solar radiation. The heat transfer in metal porous foams has found many industrial applications such as heat exchangers [2] and electronic components [3]. The radiation heat transfer of nanofluids has found applications in solar systems for direct absorption of solar radiation as discussed in Luo et al., Karami et al. and Menbari and Alemrajabi [4–6].

Different aspects of the convective heat transfer of nanofluids have been studied in many previous studies. For instance, Sun and Pop [7] have studied the free convective heat transfer of nanofluids in a porous triangle cavity. Ghalambaz et al. [8] have studied the effect of presence of nanoparticles on the convective heat transfer of nanofluids in a cavity filled with high conductive metal porous foams. Noghrehabadi et al. [9–11] have analyzed the free convective heat transfer of nanofluids in the boundary layer. Ghalambaz and Noghrehabadi [12], Ghalambaz et al. [13] as well as Zargartalebi et al. [14,15] have studied the effect of Brownian motion and thermophoresis forces on the boundary later natural convective heat transfer of nanofluids in porous media. Sheremet and Pop [16] have examined the conjugate heat transfer effects on the natural convective heat transfer of nanofluids. Sheremet et al. [17] have examined the effect of presence of nanoparticles and different thermal boundary conditions [18] on the natural convective heat transfer of nanofluids in a cavity filled with a porous medium.

The radiation effect and viscous dissipation are two important aspects of heat transfer in porous media, which were well studied in previous researches. Saeid and Pop [19] examined the effect of viscous dissipation on the natural convection heat transfer in a porous cavity. The authors [19] reported that the Nusselt number at hot wall is a decreasing function of the viscous dissipation parameter (Eckert number). Hussain and Pop [20] have studied the radiation effects over an inclined plate embedded in porous media. Mahdy and Chamkha [21] have examined the effect of viscous

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dissipation on the mixed convection in porous media. Considering the nanofluids in porous media, RamReddy et al. [22] and Chamkha et al. [23] have examined the effect of viscous dissipation on the boundary layer convective heat transfer of nanofluids. Rashad et al. [24] have studied the effect of viscous dissipation on the natural convective heat transfer of nanofluids assuming a homogeneous distribution of nanoparticles in the nanofluid and porous media.

Influences of skin friction coefficient, Brownian and thermophoresis forces on the third grade nanofluid are studied by Hussian et al. [25]. They have considered thermal radiation and MHD flow applicable in engineering issues such as heat exchangers and solar collectors. Shehzad et al. [26], have examined the effects of thermal radiation and internal heat generation in a nanofluid over a stretching surface. In another study, Shehzad et al. [27] have examined the effect of MHD (Magneto-hydro-Dynamic) flow on the Oldroyd-B nanofluid.

Recently, Makinde et al. [28] have investigated the MHD flow in a porous medium including the radiation effects. They examined the influence of viscous dissipation and magnetic field on the heat transfer over a vertical flat plate. The results show that boosting of magnetic field and Eckert number reduces heat transfer rate. Makinde [29] surveyed boundary layer flow about a flat plate in the presence of viscous dissipation effect for different types of nanofluids. Moreover, different types of water base nanofluids including Al_2O_3 and Cu in a porous medium have been examined over a flat plate by Motsumi and Makinde [30] and in a pipe by Khamis and Makinde [31]. The results indicate that the nanofluid containing Cu nanoparticles produces better heat transfer enhancement.

The review of the literature shows that the effect of viscous dissipation and radiation effects for nanofluids considering a non-homogenous model, incorporating the Brownian motion and thermophoresis forces, have not been addressed yet in a cavity. The present study aims to examine the influence of the viscous dissipation and radiation effects on the natural convective heat and mass transfer of nanofluids in a square cavity using the non-homogeneous model of nanofluids by employing the Buongiorno's mathematical model.

2. Basic equations

Consider the free convection flow of a nanofluid in a square cavity of size L filled with a nanofluid-saturated porous medium. There is a temperature difference between the isothermal vertical (right and left) walls while the horizontal walls (top and bottom) are well insulated. The cavity walls are assumed rigid and impermeable. The left vertical wall is assumed at the constant high temperature of T_h while the right vertical wall is at low temperature of T_c. A schematic representation of physical model, boundary conditions and the coordinate system is illustrated in Fig. 1.

It is assumed that the nanoparticles are well dispersed in the base fluid and the suspension is stable due to employed surface charges methods or presence of surfactants, which prevents nanoparticles from agglomeration and deposition on the porous matrix [32,33]. Further, the following assumptions are applied:

(a) Porous medium is saturated with a nanofluid fluid
(b) The fluid is assumed to be gray emitting and absorbing but non-scattering
(c) The fluid and medium are in local thermal equilibrium everywhere inside the medium.

The Darcy–Boussinesq approximation is employed. Homogeneity and local thermal equilibrium in the porous medium are assumed. We consider a medium which its porosity is denoted by ε and permeability by K. The following are the four field equations for invoking the conservation of total mass, momentum, thermal energy, and nanoparticles, respectively (see [32–34])

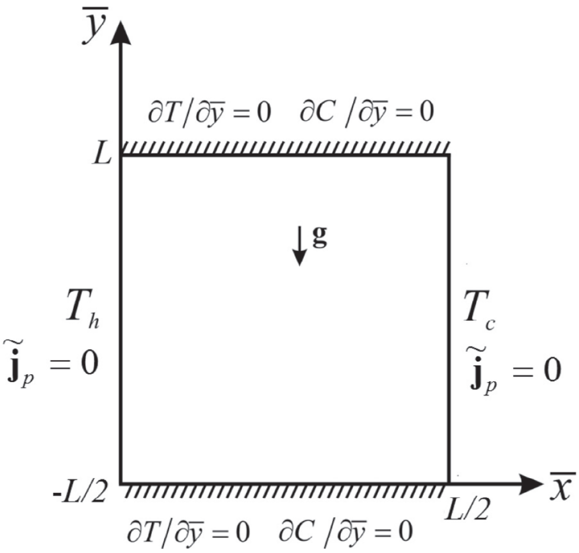

Fig. 1. Physical model and coordinate system.

$$\nabla\cdot V=0, \tag{1}$$

$$0=-\nabla P-\frac{\mu}{K}V+[C\rho_p+(1-C)\rho_{f0}(1-\beta(T-T_c))]g, \tag{2}$$

$$\sigma\frac{\partial T}{\partial t}+(V\cdot\nabla)T=\alpha_m\nabla^2T+\delta\left(D_B\nabla C\cdot\nabla T+\frac{D_T}{T_c}\nabla T\cdot\nabla T\right)-\nabla\cdot q_r+\Phi, \tag{3}$$

$$\rho_p\left(\frac{\partial C}{\partial t}+\frac{1}{\varepsilon}(V\cdot\nabla)C\right)=-\nabla\cdot j_p, \tag{4}$$

where V is the Darcy velocity vector, T is the fluid temperature, C is the nanoparticle volume fraction, t is the time, p is the fluid pressure, $\mathbf{g}$ is the gravity vector, D_B is the Brownian diffusion coefficient, D_T is the thermophoretic diffusion coefficient, $j_p=-\rho_p\left[D_B\nabla C+\left(\frac{D_T}{T_c}\right)\nabla T\right]$ is the nanoparticles mass flux, ρ_{f0} is the reference density of the fluid. In the above equations, α_m, μ, ρ_p denote the effective thermal diffusivity of the porous medium, the dynamic viscosity, nanoparticle mass density, respectively. δ and σ are quantities defined by $\delta=\frac{\varepsilon(\rho c_p)_p}{(\rho c_p)_f}$ and $\sigma=\frac{(\rho c_p)_m}{(\rho c_p)_f}$. C_p is the heat capacity at constant pressure, $(\rho c_p)_f$ is heat capacity of the base fluid, $(\rho c_p)_p$ is effective heat capacity of the nanoparticle material, $(\rho c_p)_m$ is effective heat capacity of the porous medium, β is the coefficient of thermal expansion, q_r is the radiation flux and Φ is the viscous dissipation term.

The flow is assumed to be slow so that the advective term and the Forchheimer quadratic term do not appear in the momentum equation. In keeping with the Boussinesq approximation and an assumption that the nanoparticle concentration is dilute, and with a suitable choice for the reference pressure, we can linearize the momentum equation and write Eq. (2) as

$$0=-\nabla P-\frac{\mu}{K}V+[C(\rho_p-\rho_{f0})+\rho_{f0}(1-\beta(T-T_c)(1-C_0))]g. \tag{5}$$

We consider the Rosseland approximation for radiation [30]

$$q_r=-\frac{4\sigma_{SB}}{3a_R}\left(\frac{\partial T^4}{\partial\overline{x}}+\frac{\partial T^4}{\partial\overline{y}}\right) \tag{6}$$

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