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Influences of radiative characteristics on free convection in a saturated porous cavity under thermal non-equilibrium condition

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ABSTRACT

The present work numerically examines the effect of thermal radiation from the solid phase on the thermal and flow field inside a porous medium by investigating free convection within a saturated porous cavity. A local thermal non-equilibrium (LTNE) model is used to represent the energy transport for the solid and fluid phases. The heat flux caused by the thermal radiation is obtained by solving the radiation transfer equation (RTE), so the detailed influence of the radiative characteristics can be analyzed. All the dimensionless governing equations together with the corresponding boundary conditions are solved numerically by Chebyshev collocation spectral method. The results are reported in terms of streamlines, isotherms and average Nusselt numbers for different radiative characteristics such as the conduction-radiation interaction parameter (Pl), the optical thickness (τ_L), the scattering albedo (ω), and the emissivity of the walls (ε_W). It is found that the thermal radiation plays an important role on the fluid flow and heat transfer for the buoyancy dominated flow. Substantial changes occur in heat transfer and flow field when Pl, τ_L, ω and ε_W vary in the specified ranges. The overall heat transfer is increased with decreasing of Pl and τ_L, as well as the increasing of ε_W, however, they are not very sensitive to the change of ω.

1. Introduction

Porous media can be used to enhance combined convective-radiative heat transfer in many advanced thermal energy systems operating at high temperature, such as combustion chamber, furnace, nuclear reactor, fluidized bed heat exchangers, solar collectors, etc. Owing to the existing of porous media, the solid phase of porous medium absorbs and emits radiant energy as well as transfers heat by convection with the surrounding fluid phase. To understand the combined convective-radiative heat transfer in porous media, many researchers have done a lot of works.

A large number of works are focused on the influence of radiation on the convection using the Rosseland assumption and local thermal equilibrium assumption [1–8]. Lately, using these two assumptions, Makinde et al. [9] studied the effect of temperature-dependent viscosity on the heat and mass transfer in nonlinear magnetohydrodynamic (MHD) boundary layer flow past a vertical porous plate in the presence of a magnetic field, thermal radiation and chemical reaction. Jamal-Abad et al. [10] investigated the convection-radiation heat transfer in a solar air-heater filled with a porous medium. Ghalambaz et al. [11] studied 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. López et al. [12] numerically investigated the heat transfer and entropy generation in a MHD flow of nanofluid through a porous vertical microchannel with nonlinear radiative heat flux. Bhatti et al. [13] studied the combined effects of thermo-diffusion and thermal radiation on Williamson nanofluid over a porous stretching sheet. Obviously, the solving of radiative transfer is simplified using Rosseland approximation in above mentioned references. It is reasonable and convenient to evaluate the divergence of radiative heat flux by using Rosseland approximation in an optically thick medium. However, in order to get more accurate radiative heat flux for energy equation and investigate more complicated cases of different participating media, solving the radiative transfer equation (RTE) is necessary. Based on this view, Talukdar et al. [14] investigated the combined radiation and convection heat transfer in a porous medium confined between gray isothermal parallel plates. The effects of the extinction coefficient, the scattering albedo, the conduction-

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radiation interaction parameter and the boundary emissivity on the Nusselt number, temperature and heat flux distributions had been numerically studied. Elgazery [15] studied the unsteady free convection with heat transfer from an isothermal vertical flat plate to a non-Newtonian fluid saturated porous medium. The effects of radiation and magnetic field parameters on the flow and heat transfer had been fully analyzed. Abdesslem et al. [16] carried out a numerical study of coupled fluid flow and heat transfer by transient natural convection and thermal radiation in a porous bed confined between two-vertical hot plates and saturated by a homogeneous and isotropic fluid phase. The effects of radiative properties such as the absorption coefficient, the scattering coefficient and the scattering albedo on fluid flow and heat transfer behavior inside the porous material had been investigated. However, all above researches were conducted based on the local thermal equilibrium (LTE) assumption. For the porous media, if the heat exchange between the solid and fluid phases is big enough, the local temperature difference between these two phases will be negligible, then the LTE assumption based on single energy equation model is valid. Otherwise, the two energy equations, say, the local thermal non-equilibrium (LTNE) model is necessary. Particularly in high temperature applications, the thermal radiation from the solid phase may lead to substantial heat transfer exchange between the fluid and solid phases within the porous media. Because of this reason, Yasser Mahmoudi [17] numerically examined the effect of thermal radiation from the solid phase on the fluid and solid temperature fields inside a porous medium by considering a forced convection heat transfer process within a pipe filled with a porous material. The effect of radiation from the solid phase on the fluid and solid temperature fields was analyzed through porosity, solid-to-fluid thermal conductivity ratio, Darcy number and inertia parameter. The RTE was solved by the discrete ordinate method (DOM) to obtain the radiative heat flux in the porous medium. The results demonstrated that ignoring the effect of thermal radiation from the solid phase would lead to a substantial error in prediction of the solid and fluid temperature fields. The solid and fluid temperature fields obtained for the radiative cases were substantially lower than those obtained for the non-radiative cases.

From the previous studies, it can be seen that very few investigations have been made to focus on the effects of radiation and LTNE problems in porous media. Furthermore, to the authors' best knowledge, no study has been made to consider the effects of the radiative characteristics such as the conduction-radiation interaction parameter, the optical thickness, the scattering albedo and the boundary emissivity on free convection heat transfer through porous media using the LTNE model so far. The main objective of the present work is to present a numerical study on the effects of the radiative characteristics on Nusselt number, thermal and flow distributions by solving the coupled continuity, momentum, energy and radiative transfer equations using the LTNE model. This paper is organized as follows. The problem description, governing equations and boundary conditions are presented in Section 2. Section 3 describes the numerical method and the solution strategy. The results and discussions are presented in Section 4. In this section, the effects of various parameters on the flow field, temperature fields are analyzed. Further, the convective Nusselt numbers and the radiative Nusselt numbers are also analyzed. Finally, Section 5 gives conclusions.

2. Geometrical configuration and governing equations

A schematic representation of the physical model and the coordinate system is given in Fig. 1. The cavity is filled with a fluid-saturated porous medium. The porous medium is considered as a homogeneous, isotropic, and participating medium that can emit, absorb, and isotropically scatter radiative energy, and the fluid is assumed to be transparent. The fluid and porous medium are everywhere in local thermal non-equilibrium. The left and right vertical walls of the cavity are maintained at constant high and low temperatures T_h and T_c,

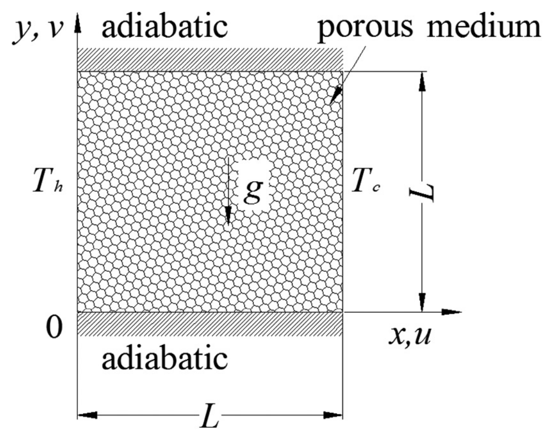

Fig. 1. Physical model and coordinate system.

individually. The top and bottom walls are all adiabatic. All of the bounding walls are assumed to be gray diffusive surfaces, with constant emissivity and reflectivity. The fluid is Newtonian and assumed to be a Boussinesq one. The Darcy flow model is adopted to consider the fluid flow.

2.1. Governing equations

Governing equations include the continuity equation, the momentum equation, the energy equations for fluid phase and solid phase respectively, as list bellow in sequence.

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

$$\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = \frac{\rho_f g \overline{\beta} K}{\mu}\frac{\partial T}{\partial x} \tag{2}$$

$$\phi(\rho c_p)_f \frac{\partial T_f}{\partial t} + (\rho c_p)_f\left(u\frac{\partial T_f}{\partial x} + v\frac{\partial T_f}{\partial y}\right) = \phi\lambda_f\left(\frac{\partial^2 T_f}{\partial x^2} + \frac{\partial^2 T_f}{\partial y^2}\right) + h(T_s - T_f) \tag{3}$$

$$(1-\phi)(\rho c_p)_s \frac{\partial T_s}{\partial t} = (1-\phi)\lambda_s\left(\frac{\partial^2 T_s}{\partial x^2} + \frac{\partial^2 T_s}{\partial y^2}\right) + h(T_f - T_s) - \frac{1}{(\rho c_p)_s}\nabla q^R \tag{4}$$

Since the fluid is assumed to be transparent, the radiative flux divergence ∇q^R only appears in the solid energy equation. ∇q^R is obtained from the radiative heat transfer equation.

$$\nabla q^R = \kappa_a\left(4\pi I_b - \int_{4\pi} I d\boldsymbol{\Omega}\right) \tag{5}$$

$$\frac{dI(\boldsymbol{r},\boldsymbol{\Omega})}{ds} = \kappa_a I_b(\boldsymbol{r}) - (\kappa_a + \kappa_s)I(\boldsymbol{r},\boldsymbol{\Omega}) + \frac{\kappa_s}{4\pi}\int_{4\pi} I(\boldsymbol{r},\boldsymbol{\Omega}')\Phi(\boldsymbol{\Omega},\boldsymbol{\Omega}')d\boldsymbol{\Omega}' \tag{6}$$

The meanings of all variables can be found in nomenclature. In order to transform the above governing equations into dimensionless ones, the dimensionless variables can be defined as:

$$X = \frac{x}{L},\ Y = \frac{y}{L},\ S = \frac{s}{L},\ U = \frac{uL}{(\rho c_p)_f/\lambda_f},\ V = \frac{vL}{(\rho c_p)_f/\lambda_f},\ \tilde{t} = \frac{\alpha}{L^2}t,$$
$$T_0 = \frac{(T_h + T_c)}{2},\ \theta_s = \frac{T_s - T_0}{T_h - T_c},\ \theta_f = \frac{T_f - T_0}{T_h - T_c},\ \delta = \frac{T_h - T_c}{T_0},\ \tilde{I} = \frac{\pi I}{\sigma T_0^4},$$
$$\Theta = \theta_s\delta + 1,$$
$$G = \int_{4\pi}\frac{\tilde{I}}{\pi}d\Omega,\ \beta = \kappa_a + \kappa_s,\ \omega = \frac{\kappa_s}{\beta},\ \tau_L = \beta L \tag{7}$$