The Role and Effects of Thermal Radiation on the Non-equilibrium Heat Transfer in a Porous Filled Enclosure

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Abstract. In this paper, the temperature differential between the solid and liquid phases in considering of combined conduction-convection-radiation heat transfer in porous media is investigated. Simultaneous solution of the solid and fluid energy equations encompasses local thermal nonequilibrium, with volumetric radiative heat flux needed in the solid-phase energy equation. The two energy equations together with the radiative heat transfer equation are simultaneously solved using the Chebyshev spectral method. The influences of the Planck numbers, the optical thicknesses, the scattering albedos, and the emissivities of the bounding walls on the thermal behavior are investigated. The results show that: (1) When $Pl$ increases above 20, the effect of radiation on the flow and thermal field can be ignored. (2) Changing $\tau_L$ has a significant effect on the solid phase temperature while, the effect is little on the fluid phase temperature. (3) For $\omega = 1.0$, the distribution of $\theta_s - \theta_f$ seems to be centrally symmetric. (4) $\theta_s - \theta_f$ are always positive except for $\omega = 1.0$.

Keywords: Thermal radiation, Porous cavity, Non-equilibrium heat transfer, Temperature differential.

1. Introduction

Porous medium has been widely adopted in the high temperature engineering applications, such as porous media combustion [1], fire barriers [2], solar thermal conversion [3], and solar hydrogen production [4]. When temperature is high, the radiation is the most important factor in heat transfer and its accurate prediction has a usually meaning to the design and optimized these advanced engineering systems, which has received lots of attention.

In the investigation of heat transfer in the porous medium, two major models, i.e., the model of local thermal equilibrium (LTE) and the model of the local thermal non-equilibrium (LTNE) are widely utilized. In order to research the heat transfer of porous materials at elevated temperature, a great deal of research has been done using LTE model. A portion of the works used the Rosseland approximation to study the influence of radiation. For examples, Nield and Kuznetsova [5] analysed a coupled conductive-convective-radiative problem in a porous channel. Dehghan et al. [6] solved the coupled convective-radiative heat transfer in heat exchangers which are full of porous medium to predict the thermal performance. Astanina et al. [7] investigated the combination of natural convection and heat radiation fills a square porous cavity with temperature dependent viscosity fluid. Rashidi et al. [8] studied the influence of radiative parameters on the pressure drops and heat transfer rates in the porous
solar heat exchangers. Besides, with the interests of the magnetohydrodynamic (MHD) flow, Tak et al. [9] and Hayat et al. [10] studied the MHD flow within the porous medium with the participation of radiation under Rosseland approximation. In the above studies, the Rosseland approximation was used to simplify the solution of radiative transfer, and as everybody knows that Rosseland approximation is reasonable only in the case of optical thick media. To obtain more accurate heat flux radiated by the solid skeleton and to study the heat transfer in more complex radiation participating media, we need to solve the radiative transfer equation (RTE). For these purposes, Talukdar et al. [11] have done many numerical studies on the coupled radiative-convective heat transfer in a porous medium surrounded by two parallel gray plates with constant temperature. The influences of the conduction and radiation interactive parameters, extinction coefficients, scattering albedo, and wall emissivity on the Nusselt numbers and thermal field were investigated. Elazar [12] numerically investigated an unsteady natural convective heat transfer in the porous medium saturated with non-Newtonian fluid. The influences of magnetic and radiative characteristics on the thermal and flow field have been analysed. Abdeslam et al. [13] numerically investigated a transient convection coupled with radiation in porous beds saturated with an isotropic and homogeneous fluid. The influences of radiation characteristics, for instance the scattering coefficients, scattering albedo and absorption coefficients, on flow and thermal transfer behaviours in porous medium were studied.

The model of LTE is easy to implement, however, it's not valid when the temperature differences between the two phases may be significant. In these cases, LTNE model must be adopted. To investigate the thermal performances of porous solar receivers, a number of researchers utilized the LTNE model a the optically thick approximation to simulate the radiation transmission [14-17], such as two-flux approximation, P1 approximation and Rosseland approximation. However, the studies involving the LTNE model together with radiation by RTE solution in porous media are still limited. Chen et al. [18] analysed the transient radiation and convection coupled heat transfer in porous tube exchangers with high temperature. The influences of the average particle diameters, porosities, inlet fluid velocities, and solid skeletons thermal conductivities on the temperature difference were analysed. Mahmoudi [19] studied the influences of thermal radiation on thermal behaviors in porous pipes under a forced convection process. The influence of radiation on the thermal behaviors was analysed by the Darcy number, inertia parameter, porosity and thermal conductivity ratio. To obtain the radiative heat flux, the discrete ordinate method was used to solve the RTE. They found that neglecting radiation of the solid skeleton will lead to significant errors in predicting the solid skeleton and fluid temperatures.

Study of literature shows that a great quantity of heat transfer analyses with radiation for the porous media have been carried out. In addition, most of the previous studies utilize the LTE model. P1 and Rosseland approximation are mostly adopted to get the radiative heat flux in porous media under the large optical thickness assumption. The studies involving the LTNE model together with radiation by RTE solution in porous media are still limited. The primary objective of this investigation is for a better understanding about the influence of radiation from the solid skeleton on the temperature differential of the two phases within a porous cavity. The model of LTNE is selected to represent the internal heat transfer between the two phases (i.e., fluid and solid skeleton), and the Chebyshev collocation spectral method (CCSM) is used to solve the RTE. The influences of Planck numbers, the optical thicknesses, the scattering albedos, and the emissivities of the walls on the thermal behavior are investigated.

2. Modeling and formulation
To formulate the problem, we consider a saturated porous cavity with a Newtonian fluid as revealed in Fig. 1. The fluid flow is assumed to be a Boussinesq one and represented by the Darcy flow model. The right vertical wall of the cavity is isothermally hot, while the left wall is isothermally cold, and the horizontal walls of the cavity are adiabatic. The four walls are grey diffuse surfaces with constant emissivities and reflectivities. The solid phase of the porous media is assumed to be gray, emitting, absorbing and isotropic scattering media. The thermal radiation flux of the fluid phase is considered negligible compared with the solid skeleton.
Using the following variable transformation,

$$X = \frac{x}{L}, Y = \frac{y}{L}, S = \frac{s}{L}, U = \frac{uL}{(\rho c_p)_f/\lambda_f}, V = \frac{vL}{(\rho c_p)_f/\lambda_f}$$

$$T_0 = \frac{T_h + T_e}{2}, \theta_s = \frac{T_s - T_0}{T_h - T_e}, \theta_f = \frac{T_f - T_0}{T_h - T_e}, \delta = \frac{T_h - T_e}{T_0}, \bar{t} = \frac{\pi l}{\sigma T_0}, \Theta = \theta_s \delta + 1, \tag{1}$$

$$G = \int_{4\pi} \frac{f}{r} d\Omega, \beta = \kappa_a + \kappa_s, \omega = \frac{\kappa_s}{\beta}, \tau_L = \beta L$$

The governing dimensionless equations can be obtained [20]:

$$\frac{\partial \Psi}{\partial t} - Ra \frac{\partial \Theta_f}{\partial X} = \frac{\partial^3 \Psi}{\partial X^2} + \frac{\partial^3 \Psi}{\partial Y^2} \tag{2}$$

$$\frac{\partial \Theta_f}{\partial t} + \frac{\partial \Psi}{\partial Y} \frac{\partial \Theta_f}{\partial X} - \frac{\partial \Psi}{\partial X} \frac{\partial \Theta_f}{\partial Y} = \frac{\partial^2 \Theta_f}{\partial X^2} + \frac{\partial^2 \Theta_f}{\partial Y^2} + H (\Theta_s - \Theta_f), \tag{3}$$

$$z \frac{\partial \Theta_s}{\partial t} = \frac{\partial^2 \Theta_s}{\partial X^2} + \frac{\partial^2 \Theta_s}{\partial Y^2} + \gamma H (\Theta_f - \Theta_s) - \frac{\tau_L (1-\omega)}{\delta Pl} \left( \Theta^2 - \frac{G}{4} \right) \tag{4}$$

$$\frac{d\Phi(r, \Omega)}{\tau_L dS} = (1-\omega) \Theta^4 - \frac{\Phi(r, \Omega)}{4\pi} + \omega \int_{4\pi} \frac{\hat{f}(r, \hat{\Omega}) \Phi(\Omega, \hat{\Omega}) d\hat{\Omega}}{4\pi} \tag{5}$$

In the above equations, $Ra$ is the Rayleigh numbers, $Pl$ is the Planck numbers, $H$ is the interphase heat transfer coefficients, $\gamma$ is the ratios of thermal conductivity, $z$ is the ratios of thermal diffusivity and $\Psi$ is the stream function, which are given as
\[
Ra = \frac{gK\beta(T_h - T_c)L}{\nu\left(\frac{\rho c_p}{f}\right) / \lambda_f}, \quad Pl = \frac{\lambda_s / L}{4\sigma T_0^3}, \quad H = \frac{hL^2}{\phi \lambda_f}, \quad \gamma = \frac{(1 - \phi)\lambda_s}{\frac{(\rho c_p)_c / \lambda_c}{(\rho c_p)_s / \lambda_s}}.
\]

The boundary conditions together with the initial conditions in the dimensionless forms are

for \(t = 0\): \(\Psi = \theta_f = \theta_s = F = 0\)

for \(t > 0\): \(\Psi(0, Y) = \Psi(1, Y) = \Psi(X, 0) = \Psi(X, 1) = 0\)

\[
\theta_f(1, Y) = \theta_s(1, Y) = -0.5; \theta_f(0, Y) = \theta_s(0, Y) = 0.5
\]

\[
-\frac{\partial \theta_f}{\partial Y} \bigg|_{Y=0.1} + \frac{\varepsilon_w}{4\pi l\delta} \left( \Theta_s - \int_{n_w : \Omega < 0} \hat{F}(r_w, \Omega) \left| n_w \cdot \Omega \right| d\Omega \right) = 0
\]

The boundary condition for Eq. (5) is

\[
\hat{F}(r_w, \Omega) = \varepsilon_w \Theta_s \left( 1 - \frac{\varepsilon_w}{\pi} \right) \int_{n_w : \Omega < 0} \hat{F}(r_w, \hat{\Omega}) \left| n_w \cdot \hat{\Omega} \right| d\hat{\Omega}, \quad n_w \cdot \hat{\Omega} < 0
\]

3. Numerical solution

The detailed numerical method of the governing equations can be found in our previous work [20]. Thus, we briefly describe the numerical strategies and steps for solving RTE and its coupling with solid energy equation are presented.

The time derivatives of the PDEs are discretized by a semi-implicit scheme with finite difference approximation. The time step is \(\Delta t = 10^{-6}\), which satisfies the CFL (Courant-Friedrichs-Lewy) condition. The Laplacian terms (diffusion terms) are treated implicitly, while the other terms of the equations are treated explicitly. All variables, except the radiative intensity, are considered instantaneous because radiation transfers at the speed of light.

The CCSM is used for the spatial discretization of PDEs. The Chebyshev Gauss Lobatto collocation point is selected. All the governing equations are solved on one same grid system. The Schur decomposition method has been used to solve the radiative intensity matrix equations [21, 22]. The energy and radiative transfer equations can be solved at the same time, but the source term of the radiation in the solid phase energy equation doesn’t need to be calculated at every time-step, and it has been updated every 100 time-steps. The marching processes have been executed till the maximum errors of the parameters studied between the current and the previous steps are fewer than a tolerance of \(10^{-6}\). MATLAB has been used to develop the implementation codes.

4. Results and discussion

Numerical studies are carried out using different numbers of grids to get the grid independent solution. the uniform grid of 44×44 points has been selected for the following analysis for any increase beyond a set of 44×44 results in a change of less than 0.167%.
For the validation, numerical comparisons are carried out between this study and those of the published data. First, the validation is carried out by comparing the flow and thermal field with the results in reference [23] without radiation, as shown in Figure 2. A good agreement has been found. Second, the validation of radiative heat transfer in a scattering media filled grey cavity was verified in preliminary work of our team [24]. Therefore, this validation will not be repeated here.

\[ \text{Figure 2. Streamlines (top), fluid isotherms (middle) and solid isotherms (bottom) with } Ra = 1000, \gamma = 1.0, H = 10. \text{ (a) results of reference [23] and (b) the present study.} \]

The effects of the key parameters on the temperature distribution of solid skeleton and fluid phase, and the temperature differences between the two phases are studied with different Planck numbers \( Pl \), optical thicknesses \( \tau_s \), scattering albedos \( \omega \), emissivities of walls \( \varepsilon_w \). The numerical simulation is carried out with \( Ra = 1000, H = 10 \) and \( \gamma = 1.0 \).
4.1. Effect of Planck numbers

Figure 3 displays the temperature distribution curves of $\theta_f$, $\theta_s$ and $\theta_f - \theta_s$ along $X$ at medium height of $Y$ ($Y = 0.5$) with different $Pl$. It is observed from Fig. 3(a) that with increasing of $Pl$, the temperature of solid phase first increases and then decreases when $X$ exceeds a threshold value around 0.18. In contrast, the temperature for the whole interior fluid is always decreased as $Pl$ increases. The curves of temperature for fluid phase and solid skeleton are mostly overlapping respectively for $Pl=20$ and without-radiation. It can be speculated that when $Pl$ increases above 20, the influence of radiation on the flow and thermal field can be ignored.

![Graph](image)

**Figure 3.** Temperature profile along $X$ at $Y = 0.5$ with different $Pl$ as $\tau_L = 1.0$, $\omega = 0.5$, $\varepsilon_w = 0.6$.

(a) $\theta_f$ and $\theta_s$ (b) $\theta_f - \theta_s$. 
Figure 3(b) shows the distribution of $\theta_s - \theta_f$ with different Pl along $X$. It can be found that for low Pl number, i.e. $Pl=0.02$, $\theta_s - \theta_f$ is always positive and the peak temperature difference value can be get around $X=0.18$ near the hot wall. And for higher Pl numbers, these quantities start with positive values and decrease to negative along $X$. As $Pl$ increases, the value of $X$ corresponding to the maximum $\theta_s - \theta_f$ is decreased. And the maximum temperature difference between two phases is always lied near the hot wall, till the radiation is not include. Without regarding to the effect of radiation, the distribution of $\theta_s - \theta_f$ is centrally symmetric.

4.2. Effect of scattering albedos

Figure 4 displays the temperature distribution curves of $\theta_f$, $\theta_s$ and $\theta_s - \theta_f$ along $X$ at $Y=0.5$ with different $\omega$ as $Pl=0.02$, $\tau_s=1.0$, $\varepsilon_s=0.6$.

(a) $\theta_f$ and $\theta_s$ (b) $\theta_s - \theta_f$.

Figure 4 displays the temperature distribution curves of $\theta_f$, $\theta_s$ and $\theta_s - \theta_f$ along $X$ at $Y=0.5$ with different $\omega$. From Fig. 4(a), it is seen that $\theta_s$ has a slight increase in the area near the hot wall but
slightly decreased in the area near the cold wall when $\omega$ increases from 0 to 0.5. And these quantities are almost overlapping in the center region of the enclosure. When $\omega = 0.1$, $\theta_f$ varies approximately linearly with $X$. While, $\theta_f$ monotonically decreases with increasing of $\omega$, and the decreased rate of $\theta_f$ is increased when $\omega$ reaches to 1.0.

From Fig. 4(b), we can see the curves of $\theta_f - \theta_s$ obtained for different $\omega$ along $X$ at $Y = 0.5$ are very different. For $\omega = 0.0$ and $\omega = 0.1$, two peak values of $\theta_f - \theta_s$ are observed: one is around $X = 0.18$ and the other is around $X = 0.95$, and the quantities are always positive. For $\omega = 0.5$, $\theta_f - \theta_s$ approaches the maximum value around $X = 0.18$, then monotonically decreases along $X$ till the cold wall. For $\omega = 1.0$, the distribution of $\theta_f - \theta_s$ seems to be centrally symmetric, and the values of $\theta_f - \theta_s$ are negative as $X > 0.5$.

4.3. Effect of optical thicknesses

Figure 5. Temperature profile along $X$ at $Y = 0.5$ with different $\tau_l$ as $Pl = 0.02, \omega = 0.5, \epsilon_w = 0.6$.

(a) $\theta_s$ and $\theta_f$ (b) $\theta_s - \theta_f$. 
Figure 5 shows the temperature distribution curves of $\theta_f$, $\theta_s$ and $\theta_s - \theta_f$ along $X$ at $Y = 0.5$ with different $\tau_L$. As illustrated in Fig. 5(a), owing to the radiation, 70% of fluid temperature is larger than zero, and for solid phase, this value is enlarged to 80%. Changing $\tau_L$ has marked impact on the temperature field of solid skeleton, while, the effect is little on the temperature of fluid phase. As $\tau_L$ increases, the temperature of solid phase first increases and then decreases along $X$, while the threshold value of $X$ is around 0.5. Meanwhile the temperature of fluid phase is slightly decreased with the increasing of $\tau_L$.

Fig. 5(b) shows the influence of $\tau_L$ on temperature difference between fluid phase and solid skeleton along $X$ at $Y = 0.5$. It's obvious that the temperature difference is always positive along $X$ for $\tau_L = 1.0$ and $\tau_L = 5.0$. As for $\tau_L = 5.0$, it is interesting to find that the temperature difference reaches its maximum value nearby the hot wall, then decreases to a relatively small value around $X = 0.9$, after that the quantity has a small increment with increasing $X$, and decreases rapidly to zero near the cold wall. For $\tau_L = 10.0$, the trend of temperature difference distributions along $X$ is similar to that of $\tau_L = 5.0$. This phenomenon illustrates that when $\tau_L$ increases, the temperature of fluid phase is decreased faster in the thin boundary layer at the cold wall. For all the cases, the peak value of $\theta_s - \theta_f$ are increased as $\tau_L$ increases, meanwhile, the value of $X$ corresponding to the maximum $\theta_s - \theta_f$ is slightly decreased.

4.4. Effect of bounding walls emissivities

Figure 6 shows the effect of $\varepsilon_w$ on $\theta_f$, $\theta_s$ and $\theta_s - \theta_f$ along $X$ at $Y = 0.5$. It is seen from Fig. 6(a) that as $\varepsilon_w$ increases, $\theta_s$ first increases and then decreases when $X$ exceeds a threshold value, and this value of $X$ is not the center point ($X = 0.5$) but a value around 0.57. For all the cases, $\theta_f$ shows negligible change along $X$. 
Figure 6. Temperature profile along $X$ at $Y = 0.5$ with different $\varepsilon_w$ as $Pl = 0.02$, $\tau_L = 1.0$, $\omega = 0.5$.

(a) $\theta_f$ and $\theta_i$, (b) $\theta_i - \theta_f$.

As showed in Fig. 6(b), the peak temperature difference value can be get in the vicinity of the hot wall, and the temperature differences between two phase are always positive except for $\varepsilon_w = 1.0$, which have negative values near the cold wall, meaning the fluid temperature is higher than solid temperature.

5. Conclusion
The effect of radiative characteristics on the thermal field within a porous medium with the help of CSCM method is studied in this work. The model of LTNE is selected to represent the interphase heat transfer within porous medium. The radiative heat flux distribution within the porous medium is computed from the solving of the radiative transfer equation. The dimensionless temperature of fluid phase and solid skeleton, together with temperature differences between the two phases are rendered graphically. The major findings of the paper are summarized as follows:

(1) As $Pl$ increases above 20, the influence of radiation on the thermal field can be neglected.

(2) Changing $\tau_L$ has significant effect on the solid temperature, while, the effect is little on the fluid temperature.

(3) For $\omega = 1.0$, the distribution of $\theta_i - \theta_f$ seems to be centrally symmetric.

(4) $\theta_i - \theta_f$ are always positive except for $\varepsilon_w = 1.0$.

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