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Effect of thermal radiation on temperature differential in a porous medium under local thermal non-equilibrium condition

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ABSTRACT

The present work examines numerically the effect of thermal radiation from the solid phase on the fluid and solid temperature fields inside a porous medium by studying forced convection heat transfer process within a pipe filled with a porous material. The Darcy–Brinkman–Forchheimer model is utilized to represent the fluid transport within the porous medium. A local thermal non-equilibrium (LTNE), two-equation model is used to represent the energy transport for the solid and fluid phases. The radiative transfer equation is solved by discrete ordinate method (DOM) to compute the radiative heat flux in the porous medium. Two primary approaches (models A and B) are used to represent the boundary conditions for constant wall heat flux. Firstly for a fixed model, the effects of radiative heat transfer from the solid phase on the temperature profiles of the two phases are analyzed for different parameters such as porosity, Darcy number, solid-to-fluid thermal conductivity ratio and inertia parameter. Secondly, the effects of radiative heat transfer on the temperature distributions and Nusselt numbers for the two phases are examined by comparing the result obtained by application of models A and B. The results demonstrate that ignoring the effect of thermal radiation from the solid phase leads to a substantial error in prediction of the solid and fluid temperature fields and validity of the local thermal equilibrium (LTE) between the two phases. The solid and fluid temperature fields obtained for the radiative case are substantially lower than those obtained for the non-radiative case. Further, it is seen that the thermal radiation from the solid phase leads the temperature fields to the LTE condition. Depending on the pertinent parameters and compared to the non-radiative case, for the radiative case up to 50% decrease in the non-dimensional temperature differential is computed between the two phases. The Nusselt number obtained by application of model A for the radiative case is higher than those predicted for the non-radiative case. While, for model B the fluid Nusselt numbers obtained for the radiative and non-radiative cases are similar.

1. Introduction

Forced convective heat transfer in porous media has been a subject of continuing interest due to its wide range of applications such as geothermal engineering, oil recovery, solar collectors, thermal insulation, heat transfer augmentation, carbon storage, solid matrix or micro-porous heat exchangers and porous radiant burners (PRBs) [1,2]. Forced convection in a channel or pipe filled with a porous material is a good representative geometry for many of these areas. The convection heat transfer in porous media has been widely investigated experimentally [3,4] and theoretically [5–8]. Two primary models, local thermal equilibrium (LTE) and local thermal non-equilibrium (LTNE) models can be utilized to represent heat transfer in a porous medium [6,7,9–13]. The LTE model based on one-equation model is valid when the heat exchange between the solid and fluid phases is high enough, so that the local temperature difference is negligible between the two phases. This model has been utilized in various analysis of heat transfer in porous media (e.g. [14–20]). While, the LTE model simplifies the heat transfer analysis, in some applications when a substantial temperature difference exists between the two phases, the LTE model does not hold. In these situations the effects of different mechanisms that augment the internal heat exchange between the two phases cannot be neglected. In this regard, the interfacial surface and the interstitial heat transfer coefficient which are related to the internal heat exchange between the solid and fluid phases, are major factors causing heat transfer augmentation in the porous media [9,11]. Furthermore, in high temperature thermal energy systems, the convection and radiation modes of heat transfer are both important. The purpose for this technique is to use porous

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Nomenclature

a_{sf}	specific surface area (m^{-1})
C_{pf}	specific heat at constant pressure ($J\,kg^{-1}\,K^{-1}$)
d_p	particle diameter (m)
Da	Darcy number, K/R^2
F	inertia parameter defined in Eq. (7)
h	wall heat transfer coefficient
h_{sf}	fluid-to-solid heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
I	radiation intensity ($W\,m^{-2}$)
J	unit vector aligned along the pore velocity
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
K	permeability (m^2)
L	pipe length (m)
Nu	local Nusselt number
P	pressure ($N\,m^{-2}$)
P_r	Prandtl number ($\mu_f\,C_{pf}/k$)
q	heat flux ($W\,m^{-2}$)
R	pipe radius (m)
Re_p	particle Reynolds number, $\rho\,U_{in}\,d_p/\mu_f$
Re_D	Reynolds number $\rho\,U_{in}\,(2R)/\mu_f$
s	direction vector in radiative transfer equation
T	temperature (K)
T_m	mean temperature (K)
u	velocity in z-direction ($m\,s^{-1}$)
U_m	mean velocity
v	velocity in r-direction ($m\,s^{-1}$)
V	velocity vector ($m\,s^{-1}$)
r, z	cylindrical coordinates (m)

Greek symbols

ε	porosity
$\in$	emissivity
κ	solid-to-fluid thermal conductivity ratio, k_s/k_f
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
σ	Stefan–Boltzmann constant
θ	dimensionless temperature defined by $\theta = (T - T_{in})/(q_w R/k_f)$
Θ	dimensionless temperature defined as $\Theta = k_{s,eff}(T - T_{s,wall})/(q_w R)$ used in Fig. 2 for comparison of present numerical results against exact solutions of Yang and Vafai [10]
Φ	phase function
ω	scattering albedo
β	extinction coefficient
ζ	dimensionless radial length, r/R

Subscripts

b	black body
eff	effective property
f	fluid
i	direction index
in	inlet
m	mean quantity
o	outlet
rad	radiation
s	solid
w	wall

Other symbol

$\langle\rangle$	'local volume average' of a quantity

media to enhance combined convective–radiative transfer This is to save remarkable energy or to keep heat from releasing, from high temperature areas for combustion requirements in industrial furnaces, combustors and PRBs. In such applications, the solid phase absorbs and emits radiant energy while interacts by convection heat transfer with the fluid surrounding it. Thus, the thermal radiation from the solid phase may lead to substantial heat transfer exchange between the fluid and solid phases within the porous media. In this situation the two-equation, LTNE model needs to be utilized. The main objective of the present work is to analyze the effect of thermal radiation from the solid phase on the temperature differential between the two phases under LTNE condition. LTNE model has been used recently in some applications such as heat transfer augmentation [7,16,21–25], heat transfer through biological media [12,26], CO_2 storage [27], heat transfer between the solid particles and the fluid in a miniporous medium [28] and heat flux bifurcation in a porous medium [5,6,10,29–31]. The possible physical grounds of the models for the heat flux bifurcation phenomenon have been further discussed Nield [32] and Vafai and Yang [29].

The analysis of LTNE in a channel or pipe subjected to a constant wall heat flux is still being challenged, since it is not clear what boundary condition might be used as thermal boundary condition at the channel or pipe wall [9–11,33,34]. Amiri et al. [34] highlighted for the first time this problem and presented two different approaches for boundary conditions under constant wall heat flux. They reported that the constant heat flux boundary condition could be viewed in two different ways [34]. The first is to assume that the total wall heat flux being divided between the two phases based on their effective conductivities and the corresponding temperature gradients. In the second approach, each of the two phases receives an equal amount of the total heat flux at the pipe wall [34]. Designating one model over the other is not an easy issue since some previous studies validated each of the two primary models. In addition to that the mechanics of splitting the heat flux between the two phases is not yet resolved. Moreover, it is expected that various effects might cause a set of experimental results to agree with one model over the others. These effects include the variable porosity, the thermal dispersion and the wall thickness. For a pipe fully filled with a porous material which is under constant wall heat flux boundary condition, it is known that when the wall boundary has a finite thickness composed of a high conductivity material, the two phases should have the same wall temperature. Therefore, for this class of applications, the first approach is preferable. On the other hand, the second approach is anticipated to be a good representative boundary condition for applications with high wall temperatures and high temperature gradients. Jiang and Ren [35] for fully filled channel showed that when the thermal conductivities of fluid and solid phases are very similar, the fluid and the solid phases are very near local thermal equilibrium at any location in the porous media and hence different models at the wall show similar trend. While when the thermal conductivity between the fluid and solid phases are different they obtained good agreement between the second approach and the experimental data. Both of the aforementioned scenarios were examined by many researchers [3,36–40]. Amiri et al. [34] found good agreement between the numerical results using the second approach and the experimental results. Hwang et al. [41] used the first approach and found good agreement between their numerical and experimental results. Jiang et al. [42] utilized model B to study forced convection heat transfer of air in plate channels filled with glass or non-sintered steel spherical particles. Their