International Journal of Thermal Sciences 99 (2016) 228–237

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

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Effect of thermal radiation on temperature differential in micro channels filled with parallel porous media

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ARTICLE INFO

Article history:
Received 31 March 2015
Received in revised form
4 September 2015
Accepted 4 September 2015
Available online 29 September 2015

Keywords:
Radiation
Micro-channels
Numerical model

ABSTRACT

The present work examines the effect of thermal radiation from the solid phase on the fluid and solid temperature inside a porous medium by studying forced convection heat transfer process within a parallel plates porous micro-channels. The Darcy-Brinkman model is considered in the momentum equation and two energy equations are used to evaluate solid and fluid temperatures. Results are reported in terms of average Nusselt numbers and dimensionless temperature profiles as a function of Biot number (Bi), effective thermal conductive ratio (k), Darcy number (Da), accommodation coefficients (tangential momentum and thermal) and Knudsen number.

1. Introduction

In recent years, research activity in heat transfer at micro and nano scale geometries has been strongly developing due to the incredible growth of micro-electro-mechanical systems (MEMS). Several mechanical and biomedical applications have determined an increasing research interest in micro and nano flows as recently reviewed in refs [1–5,44–54]. A general introduction of the importance and development of microfluidics is reported in Ref. [1], a complete description of the fundamentals in the micro channels is provided in Ref. [2], a bio-MENS application in term of nanofluid flow in micro channels is provide in Ref. [3], a review focused on molecular momentum transport at the fluid–solid interface mainly related to microfluidic and nanofluid in micro or nano–electro-mechanical system (MEMS or NEMS) is preform in Ref. [4], a survey of existing methods for the characterization of mixing and flow in micro channels, micro mixers and micro reactors is presented in Ref. [5], a note on unsteady hydromagnetic free convection from a vertical fluid saturated porous medium channel is preform in Ref. [44], a complete description of non-Darcy fully developed mixed convection in a porous medium channel with heat generation or absorption and hydromagnetic effects is presented in Ref. [45], a complete description on flow of two-immiscible fluids in porous and non-porous channels is preform in Ref. [46], a general introduction of unsteady laminar hydromagnetic flow and heat transfer in porous channels with temperature-dependent properties is presented in Ref. [47], a description of laminar hydromagnetic mixed convection flow in a vertical channel with symmetric and asymmetric wall heating conditions is preform in Ref. [48], a study on mixed convection in a vertical porous channel is presented in Ref. [49], a complete description of unsteady oscillatory flow and heat transfer in a horizontal composite porous medium channel is preform in Ref. [50], a study on non-Darcy forced convection through a wavy porous channel using CuO nanofluid is presented in Ref. [51], a numerical simulation of non-Darcy forced convection through a channel with non-uniform heat flux in an open cavity using nanofluid is presented in Ref. [52], a review Hartmann Newtonian radiating MHD Flow for a rotating vertical porous channel immersed in a Darcian porous regime and given an exact solution is presented in Ref. [53] and a numerical analysis of a nanofluid forced convection in a porous channel for a new heat flux model in LTNE condition is preform in Ref. [54].

2. Theoretical modeling

2.1. Governing equation

Dimension of both the channel and the porous medium in normal direction to the fluid flow is large enough to ensure the two dimensionality of the problem. The distance between walls is 2H. A fluid with uniform velocity U_{in} and with temperature T_{in} inter the

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http://dx.doi.org/10.1016/j.ijthermalsci.2015.09.005
1290-0729/

channel at x = 0. The fluid flow through the channel filled with the porous medium, is subject to a constant heat flux boundary condition q_w. Just the radiation heat transfer from solid phase be considered, and the fluid phase assumed to be non-radiative comparison to the solid radiation [6–17]. In modeling of porous radiant burners [6–17], when the gas phase is reactive and the temperatures are also very high, it has been stated that the gas radiation is negligible compared to the soled radiation. Further, it has been shown previously in modeling of porous heat exchanger [18] that the gas radiation does not have a considerable effect on the steady state thermal behavior of porous heat exchangers. All thermo physical properties of the solid and the fluid phases are assumed constant [6,7,17,18]. The porous material is assumed to be gray, emitting, absorbing and isotropically scattering. Further, the flow is assumed to be steady and incompressible. The fluid flow is represented by the Darcy–Brinkman flow model. Flowed assumed to be Darcy flow videlicet a linear relationship between volumetric flow rate (Darcy velocity) and pressure (or potential) gradient dominant at low flow rates. Natural convection is ignored. The thermo-physical properties such as porosity, specific heat, density, thermal conductivity and radiative properties of the solid phase are assumed to be constant. Based on these assumptions, the steady-state volume averaged governing equations:

Continuity:

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

Momentum:

$$\frac{\mu}{K}u - \mu_e\frac{\partial^2 u}{\partial y^2} = G \tag{2}$$

Where G is the ratio of pressure drop, $G = -\frac{\Delta p}{l}$, L is the channel length, K is the permeability of porous medium and μ_e is the effective dynamic viscosity.

Energy equation for the fluid phase:

$$\rho_f C_{p,f} u\frac{\partial T_f}{\partial x} = \varepsilon K_f\frac{\partial^2 T_f}{\partial y^2} + h_v\left(T_s - T_f\right) \tag{3}$$

The term h_v is the volumetric heat transfer coefficient and it is the convective heat transfer between solid and fluid inside the porous medium at solid–fluid interface i.e. the interstitial heat transfer coefficient [19]. In this study h_v is assumed constant inside the domain.

Energy equation for solid phase:

$$(1-\varepsilon)K_s\frac{\partial^2 T_s}{\partial y^2} = h_v\left(T_s - T_f\right) - \nabla(q_{rad}) \tag{4}$$

Since, the fluid is assumed to be transparent, the radiative flux divergence$\nabla(q_{rad})$ only appears in the solid energy equation. For non-radiative computation the contribution of the radiative term $\nabla(q_{rad})$ is set to be zero.

For radiation purposes, the porous medial was considered as diffuse gray body and the fluid is assumed to be non-radiative. Radiation flux is calculating by using radiation transfer equation (RTE) in enclosure absorbing-emitting-scattering medium. Then the heat source term$\nabla(q_{rad})$ due to solid thermal radiation Eq. (4) is obtained from the radiation heat transfer equation. The general equation of radiation transfer for an absorbing, emitting and anisotropically scattering medium along direction vector s is written as [8,14]:

$$s\cdot\nabla I = \beta\left[(1-\omega)I_b - I + \frac{\omega}{4\pi}\int_{4\pi} I_{(S_i)}\varphi_{(S_i,s)}d\Omega_i\right] \tag{5}$$

$$\nabla q_{rad} = \beta(1-\omega)(4\pi I_b - \int_{4\pi} I_{(s)}d\Omega \tag{6}$$

Whit boundary condition given by Ref. [19]:

$$I_{(z=0)}\frac{\sigma}{\pi}T_{i,surroding}{}^4 I_{(z=l)} = \frac{\sigma}{\pi}T_{o,surroding}{}^4 \tag{7}$$

In the above ω is the scattering albedo, φ is the phase function, σ is the Stefan–Boltzmann constant and I is the radiation intensity and radiation intensity of black body is expressed as $I_b = \frac{\sigma}{\pi}T^4{}_s$ [8,14]. In the present work extinction factorβ and scattering albedo ω are set to be 27 cm and 0.8, respectively [20] $T_{i,surroding}$ is the temperature of surrounding at the inlet of the channel. Assumed is that the surrounding temperature equal to the fluid inlet temperature as $T_{i,surroding} = T_{i,f}$ [8,20]. Further $T_{o,surroding}$ is the surrounding temperature at the outlet of the channel that are assumed to be 300 K [8,14].

It shod be underlined, as also report in Ref. [20] that the important point is whether Knudsen number has a value for which it is acceptable to employ the continuum model whit velocity slip. The usual continuum approach is applied and the rarefaction of the gas are modeled with the first order velocity slip and temperature jump condition at the fluid–solid interface [2,21–23].

For momentum Eq. (2), the first order boundary condition are [2,23–25].

At y = H

$$U_{slip}(y = H) = \eta_0\frac{2-\sigma_v}{\sigma_v}\lambda\frac{\partial u}{\partial y}\bigg|_{y=H} \tag{8}$$

Where η_0 is a corrective coefficient which depend on the gas and the wall surface [2,26,27], U_{slip} is the slip velocity and λ is the molecular mean free path and σ_v is the tangential momentum accommodation coefficient.

The symmetry condition at y = 0

$$\frac{\partial u}{\partial y}\bigg|_{y=H} = 0 \tag{9}$$

$$K_{s,eff} = (1-\varepsilon)K_s \quad \text{and} \quad K_{f,eff} = \varepsilon K_f \tag{10}$$

Where ε is porosity.

2.2. Boundary condition for the non-radiative case

Due to the symmetry of the problem, only the upper half of the channel is considered. At y = 0 symmetry causes the gradients of the axial velocity and temperature in y direction to be zero. At the entrance, x = 0, v = 0, $T = T_{in}$ and $u = u_{in}$ while at the exit, x = L, the gradients of v, u and T in x direction are zero. In summary, the boundary conditions are summarized in Table 1 [28–30].

2.3. Boundary condition for the radiative case

The boundary conditions utilized for the axial and radial momentum equations and the boundary condition for the energy equation of the fluid phase are similar to the non-radiative case, which are presented in Table 1. For the solid energy equation, the inlet and outlet boundary conditions are expressed as [8,9].