Heat Transfer Enhancement in Channel Partially Filled with Porous Material

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Abstract: In this research, fluid flow and heat transfer in a parallel plates channel, partially filled with porous material, have been considered. The Darcy-Brinkman model and the Navier-Stokes equations for flow solution have been employed in porous and free fluid domains respectively. The walls of the channel held at uniform temperature and the local thermal equilibrium assumption is also used in porous media. The important point in this study is implementation of interface boundary condition between free fluid and porous domain. Numerical finite volume code with SIMPLE algorithm has been developed and the influences of suitable non-dimensional parameters such as Darcy and Reynolds number on Nusselt number has been discussed thoroughly. The effect of porous layer thickness on flow pattern and heat transfer is also discussed. The outcomes of the numerical calculation show good agreement with the analytical results for fully developed flow case.

Key-Words: Forced convection heat transfer – Porous media – local thermal equilibrium – Numerical solution

1 Introduction

Analysis of fluid flow and heat transfer in porous medium has been a subject of continuous interest during the past decades, specifically forced convection heat transfer in a channel or duct fully or partially packed with a porous material is of considerable technological interest. This is due to the wide range of applications such as direct constant heat exchangers, electronic cooling, heat pipes, etc. In many of aforementioned applications Darcy model is used to represent fluid flow in porous media. This simple equation relates the averaged velocity to pressure drop through porous medium, but in wall bounded porous media because of implementation of boundary condition, the Darcy model has no reality and another form of momentum equation should be used. In this work, fluid flow and heat transfer in a parallel plates channel involving free fluid domain and porous domain are treated while the flow within the porous region is modeled by the Brinkman-Forchheimer-extended Darcy formulation, and the flow in free region is described by the Navier-Stokes equations. Thermally developing forced convection in a porous medium with walls at constant temperature has been studied by Nield et al. [1].They assumed that the Peclet number was sufficiently large so that axial conduction could be neglected. In this study, presents two definitions for Peclet number corresponding the two specified zones. Koh and Colony [2], performed a numerical analysis of the cooling effectiveness of a heat exchanger containing a conductive porous medium, while Koh and Stevens [3], conducted an experimental investigation for the same problem. It was shown that for the case of a fixed wall temperature the heat flux at the channel wall can be increased by over three times by using a porous material in the channel. Rohsenow and Hartnett [5] presented a constant Nusselt number for the fully developed region in a porous medium bounded by two parallel plates, based on the Darcy flow model. To consider the effect of a solid boundary, Kaviany [6], performed a numerical study of laminar flow through a porous channel bounded by isothermal plates based on the

generalized model developed in Vafai and Tien [7].
In this study, we concentrate on the case of a parallel plate channel partially filled with porous material, with walls at constant temperature. The Darcy-Brinkman model and the Navier-Stokes equations have been employed in porous domain and free fluid domain respectively. The effects of porosity, thickness of porous layer, conductivity of porous material, Darcy and Reynolds number on Nusselt number, pressure drop, temperature, convection coefficient and velocity in developing and developed sections of parallel plates channel are studied thoroughly.

2 Governing Equations

This research is focused on the case of a parallel plate channel partially filled with porous material. The geometry of problem is shown in Fig.1. Upper and lower walls held on constant temperature and they are impermeable. The height of channel is considered H.

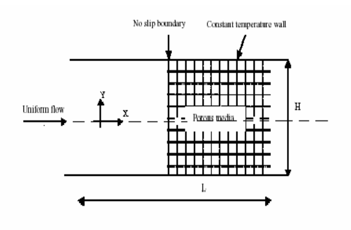

Fig. 1: Geometry of problem

Governing equations for the flow in the free and porous medium according to [8, 9, 10], are given by following equations;
Mass conservation, in both the free and porous domains is given by:

$$\frac{\partial}{\partial \mathrm{X}_i}\left(\rho_f u_i\right)=0 \qquad (1)$$

where i and j are the Cartesian indexes (i, j = 1, 2), and a repeated index in a product means summation over all the index range (repeated index convention), x_i (i =1, 2) are the Cartesian co-ordinates, u_i (i = 1, 2) are the respective Cartesian velocity components, and ρ_f is the fluid density.

Energy conservation, in both the free and porous domains is defined by:

$$u_i \frac{\partial T}{\partial \mathrm{X}_i}=\left(\frac{K_a}{\rho_f C_{pf}}\right)\frac{\partial^2 T}{\partial \mathrm{X}_i^{\,2}} \qquad (2)$$

where, C_{pf} is specific heat of the fluid. Viscous dissipation effects are neglected in line with limiting in Reynolds number quantities. The quantity K_a named the apparent conductivity; it is a result of conduction in the solid material and in the fluid. If a simple "parallel" path model is assumed, K_a will be given by:

$$K_a = \varepsilon K_f + (1-\varepsilon) K_s \qquad (3)$$

where K_f and K_s are the conductivities of the fluid and solid material respectively and ε is the porosity of the porous medium. It is clear that in free medium K_a is changed to K_f because of ε =1.
Momentum equations in the free fluid domain (Navier-Stokes equations):

$$\frac{\partial}{\partial \mathrm{X}_i}\left(\rho_f u_i u_j\right)=-\frac{\partial \mathrm{P}}{\partial \mathrm{X}_j}+\frac{\partial}{\partial \mathrm{X}_i}\left(\mu_f \frac{\partial u_j}{\partial \mathrm{X}_i}\right) \qquad (4)$$

where P is the pressure, and μ_f is the dynamic viscosity.
Momentum equations in the porous domain according to Brinkman-Forchheimer equations are:

$$\frac{\partial}{\partial \mathrm{X}_i}\left(\rho_f u_i \frac{u_j}{\varepsilon}\right)=-\frac{\partial \mathrm{P}}{\partial \mathrm{X}_j}+\frac{\partial}{\partial \mathrm{X}_i}\left(\frac{\mu_b}{\varepsilon}\frac{\partial u_j}{\partial \mathrm{X}_i}\right) -\left(F\varepsilon\frac{\rho_f}{\sqrt{\kappa}}\left|V\right|+\frac{\mu_f}{\kappa}\right)u_j \qquad (5)$$

where μ_B is the Brinkman viscosity (the equivalent to the dynamic viscosity within the porous domain), κ is the permeability of the (isotropic) porous domain, and $\left|V\right|=\sqrt{u_i^{\,2}}=\sqrt{\left(u^2+v^2\right)}$ is the absolute value of the velocity and F is the Forchheimer coefficient, according to Vafai and Tien [11], this coefficient, which is used in expressing the inertial term in equation (5), depends on the Reynolds number and microstructure of the porous medium. An empirically based correlation for this coefficient can be found in ref. [12]. In this work the fluid and the material of porous media properties are being assumed to be constant, then $\mu_B = \mu_f$.

3 Boundary Conditions and Normalization

Assuming high thermal conductivity at the boundary, the temperature and velocity at wall interface is:

$T(x,H/2)=T_w$, $u(x,H/2)=0$ (6)

The symmetry condition at the center line will be:

$$\frac{\partial T}{\partial Y}(x,0)=0 \quad \frac{du}{dY}(x,0)=0 \qquad (7)$$

At the inlet of channel we have:

$T(0,y)=T_{in}$ (8)

By defining the following non-dimensional parameters:

$$X_i^* = \frac{X_i}{H}, u_i^* = \frac{u_i}{U}, P^* = \frac{P}{(\rho U^2)}$$
$$Re = \frac{\rho UH}{\mu}, Da = \frac{\kappa}{H^2}, \theta = \frac{T - T_w}{T_{in} - T_w} \qquad (9)$$

Where H is the height of the channel, U is the inlet velocity; T_w and T_{in} are the wall and the inlet temperature respectively.

Eqs.(1) to (5) in non-dimensional form is as:

$$\frac{\partial u_i^*}{\partial X_i^*} = 0 \qquad (10)$$

$$u_i^* \frac{\partial \theta}{\partial X_i^*} = \left(\frac{K_a}{C_{pf}\mu_f \, Re}\right) . \left(\frac{\partial^2 \theta}{\partial X_i^{*2}}\right) \qquad (11)$$

$$\frac{\partial}{\partial X_i^*}\left(u_i^* u_j^*\right) = -\frac{\partial P^*}{\partial X_j^*} + \frac{1}{Re} . \frac{\partial^2 u_j^*}{\partial X_i^{*2}} \qquad (12)$$

$$\frac{1}{\varepsilon} . \frac{\partial}{\partial X_i^*}\left(u_i^2 u_j^2\right) = -\frac{\partial P^*}{\partial X_j^*} + \frac{1}{\varepsilon \, Re}\frac{\partial^2 u_j^2}{\partial X_i^{*2}} -$$
$$\left(F\varepsilon \frac{1}{\sqrt{Da}}\left|V^*\right| + \frac{1}{Re . Da}\right) u_j^* \qquad (13)$$

The dimensionless forms of boundary conditions are:

$$\theta(0, Y^*) = 1 , \theta(X^*, 1) = 0 \qquad (14)$$
$$u^*(X^*, 1) = 0 , u^*(0, Y^*) = 1 \qquad (15)$$
$$\frac{\partial \theta}{\partial Y^*}(X^*, 0) = 0 , \frac{\partial u^*}{\partial Y^*}(X^*, 0) = 0 \qquad (16)$$

Free/porous domain interface boundary conditions according to [8] can be evaluated as described blew:

The local 'natural' conditions at the interface are, in their vector form:

Mass conservation

$(\rho \mathbf{V}.\mathbf{n})_f = (\rho \mathbf{V}.\mathbf{n})_p$ (17)

Where subscripts f and p refer to free fluid and porous domains, respectively, and **n** is the unit vector normal to the interface,

Normal stress continuity

$(\mathbf{n}.\mathbf{n}.\boldsymbol{\sigma})_f = (\mathbf{t}.\mathbf{n}.\boldsymbol{\sigma})_p$ (18)

Where **t** is the unit vector tangent to the interface, and

$$\sigma_{ij} = \mu\left(\frac{\partial u_i}{\partial X_i} + \frac{\partial u_j}{\partial X_i}\right) - P\delta_{ij} \qquad (19)$$

is the total stress tensor, and δ_{ij} the δ Kronecker's function.

The local 'essential' conditions at the interface are :

Velocity continuity

$(\mathbf{V})_f = (\mathbf{V})_p$ (20)

Pressure continuity

$(P)_f = (P)_p$ (21)

Eqs. (17) and (18) implicitly state that the normal and tangential stresses are fully supported by the fluid , i.e. it is assumed the porous medium itself does not participate in this balance. This simplification, although convenient, somehow lacks rigor.

4 Numerical modeling

In this study, two-dimensional laminar version of the control volume based finite volume method [13], is used. The numerical code is developed and the influence of aforementioned non-dimensional parameters on Nusselt number was discussed. Numerical method involved staggered discrete grid for solving momentum, energy, mass equations.

The UPWIND scheme has been used in numerical method and the precision of main parameters is controlled each iteration. The flow filed is obtained using SIMPLE algorithm on collocated grids [13].

The dependency of numerical results on the number of grids was also studied and the final results were independent of them.

The Nusselt number is defined as:

$$Nu = \frac{hh}{K_a} = \frac{Hq'}{K_a\left(T_w - T_m\right)} = \frac{\partial \theta}{\partial \mathrm{Y}^*}\bigg|_{y^*=1} \qquad (22)$$

Where T_m and q" are bulk temperature and heat flux respectively.

In what concerns the interface boundary conditions, the computational grid is constructed in such a way that the free/porous domain interface is located along a row of nodes. In this way, a control volume associated with a node at the interface is composed by two components, namely: one is part of the free fluid domain, and the other one is part of the porous domain. For a finite volume over the free domain, the pressure coefficient is conditioned by its free domain nodal values, while for the porous medium the pressure coefficient is obtained as the arithmetic average of its porous medium nodal values.

5 Results and Discussion

In this research there are a large number of parameters to study. We have calculated the temperature, pressure and velocity distribution and also Nusselt number and convection coefficient values. The local Nusselt number calculated from Eq. (22). The effects of Darcy and Reynolds number, porosity, thickness of porous layer and conductivity of porous material on mentioned parameters are reported in Figures 2 to 10. Figures 2 to 4 show the comparison of local Nusselt number, developed temperature and velocity plots along the channel with and without porous part, in this case Re=50, Da=0.05, ε=0.5 are considered. Figures 5 to 7 show the effects of Darcy number, Figures 8 to 10 show the effects of porosity on local Nusselt number along the channel and fully developed temperature and velocity profiles. The outcome of the numerical calculation show good agreement with analytical results for fully developed flow case reported by Nield et al. [14], and Jiang [15].

6 Conclusions

In this study numerical method is applied to investigate fluid flow and heat transfer in parallel plates channel partial filled with porous material. The Brinkman model and local thermal equilibrium assumption employed in porous medium. Numerical finite volume code is developed and the effects of Darcy number and porosity, on local Nusselt number, thermal and velocity fully developed profiles (all characters are dimensionless) are also considered. The numerical analysis indicates that the presence of porous layer may increase Nusselt number in entrance of the channel, because of increasing the longitude of developing (velocity and temperature) region, also in fully developed zone in porous medium Nusselt number has a very little decrease (as it was showed in [14, 15]), in comparison with channel without porous media, but because of axial conduction the heat transfer will be increased.

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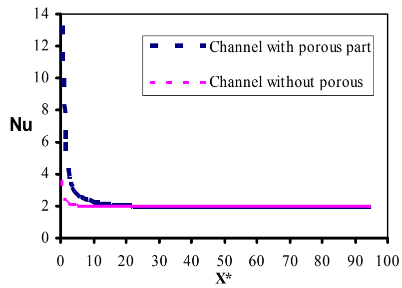

Fig. 2 Plots of Nusselt number versus dimensionless coordinate.

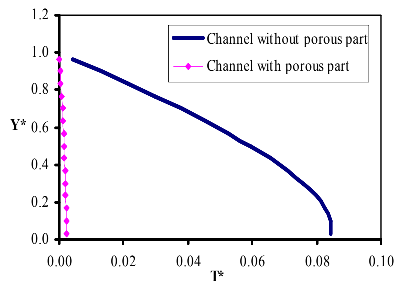

Fig. 3 Dimensionless form variation of temperature profiles in fully developed region.

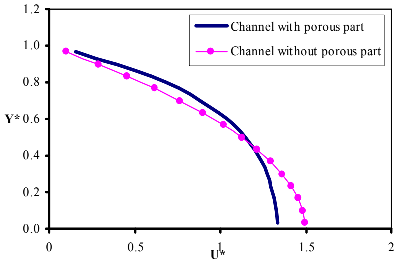

Fig. 4 Dimensionless form variation of velocity profiles in fully developed region.

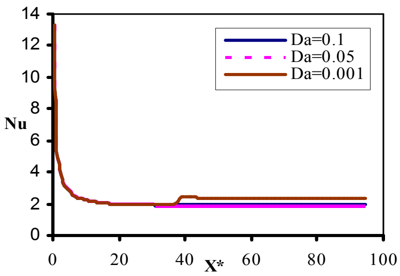

Fig. 5 Plots of Nusselt number versus dimensionless coordinate for various values of Darcy number.

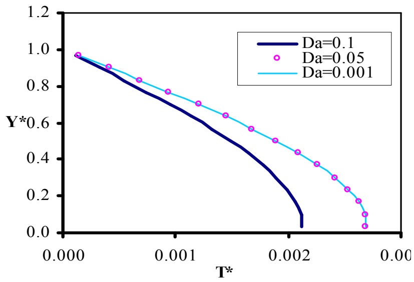

Fig. 6 Dimensionless form variation of temperature profiles in fully developed region for various of Darcy number.

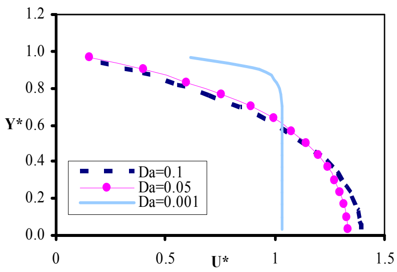

Fig. 7 Dimensionless form variation of velocity profiles in fully developed region for various of Darcy number.

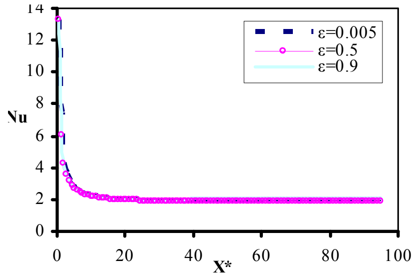

Fig. 8 Plots of Nusselt number versus dimensionless coordinate for various values of porosity.

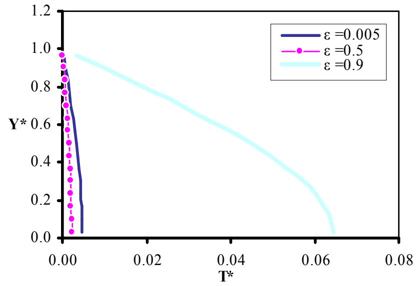

Fig. 9 Dimensionless form variation of temperature profiles in fully developed region for various of porosity.

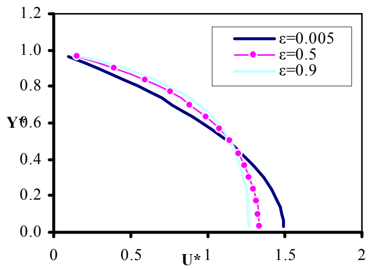

Fig. 10 Dimensionless form variation of velocity profiles in fully developed region for various of porosity.