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Effect of heat transfer in the thermally developing region of the channel partially filled with a porous medium: Constant wall heat flux

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ABSTRACT

Laminar forced convection in the thermally developing region of parallel plate channels partially filled with a porous material has been studied numerically. The parallel plates are subjected to constant wall heat flux. Porous insert is attached to both the walls of the channel with equal thickness. The flow field is assumed to be fully developed. The system is characterized by the parameters, Darcy number, *Da* and a porous fraction, γ_p defined as ratio of the porous insert thickness to the channel wall spacing. Numerical solutions have been obtained for $0 \leq \gamma_p \leq 1.0$, for $Da = 0.001$, 0.005, 0.01, 0.05 and 0.1. The non-dimensional temperature at the wall attains maximum values at a certain porous fraction. The local Nusselt number has been obtained on the porous side of the parallel plate channel.

1. Introduction

In recent times, several researchers have studied the fluid flow and heat transfer in the porous media, in view of their significant applications in situations such as enhanced recovery of oil by thermal methods, cooling of electronic components, risk assessment of disposal of nuclear waste, proton exchange membrane (PEM) fuel cells.

It is observed that, in fully filled systems results in significant pressure drop. Hence, for enhancing heat transfer partially filling is a desirable way. This can even be done by keeping the pumping expense at an appropriate level. In application of convective heat transfer in porous medium such as solid matrix heat exchangers and thermal insulation, oil recovery, geothermal engineering, heat pipes, chemical reactors, hydrogeology. Wherever it is not desirable to fully fill the system with porous medium, partially filled systems seems to be the best alternative to achieve the desired goal (Mahmoudi and Maerefat [1], Mohamad [2] and Maerefat et al. [3]).

Authors of Mohamad [2] and Pavel and Mohamad [4] observed that there is a significant increase in the Nusselt number for the case of forced convection through a pipe partially filled with porous material compared to that of a clear pipe. Numerical simulation of forced convection enhancement in a pipe by porous inserts studied by Maerefat et al. [3]. The importance of these studies show the influence of the porous insert in the pipe on the rate of heat transfer.

The slip condition at the porous-fluid interface has been considered by several authors, Beavers and Joseph [5] were the first to consider the slip condition where as Saffman [6] gave theoretical justification for the same. The conditions of the continuity of velocity and shear stresses at the interfaces have been used by Neale and Nader [7] and Vafai and Kim [8]. These interface conditions have been used by Kuznetsov [9, 10 and 11], Alazmi and Vafai [12], Satyamurty and Bhargavi [13], and Bhargavi and Satyamurty [14].

The problem of the non Darcy Brinkmann model viz., forced convection in the porous medium has been first studied by Poulikakos and Kazmierczak [15]. They studied the problem under the boundary conditions of uniform wall heat flux and constant wall temperature. Subsequently, this problem has been studied under different conditions by several authors (Kuznetsov [9, 10 and 11], Alazmi and Vafai [12], Xiong [16], Nield et al. [17], Bhargavi et al. [18] and Hooman et al. [19]).

Many investigators (Chick et al. [20], Mohamed et al. [21], Mahmoudi et al. [22] and Mahmoudi and Karimi [23]) have studied forced convection in ducts partially or fully filled with porous material under different conditions.

Though several authors studied forced convection in the porous medium and channel partially filled with a porous medium and different conditions, but aspects such as bulk mean temperature, wall temperature as a function of axial distance have not been addressed in any of these investigations. Fully developed forced convection in a parallel plate channel with a centered porous layer was studied by Cekmer et al. [24]. Bhargavi and Satyamurty [14] studied optimum porous insert configurations for enhanced heat transfer in channels. However, the problem of thermally developing region in a channel partially filled with a porous material and without using the boundary

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Nomenclature

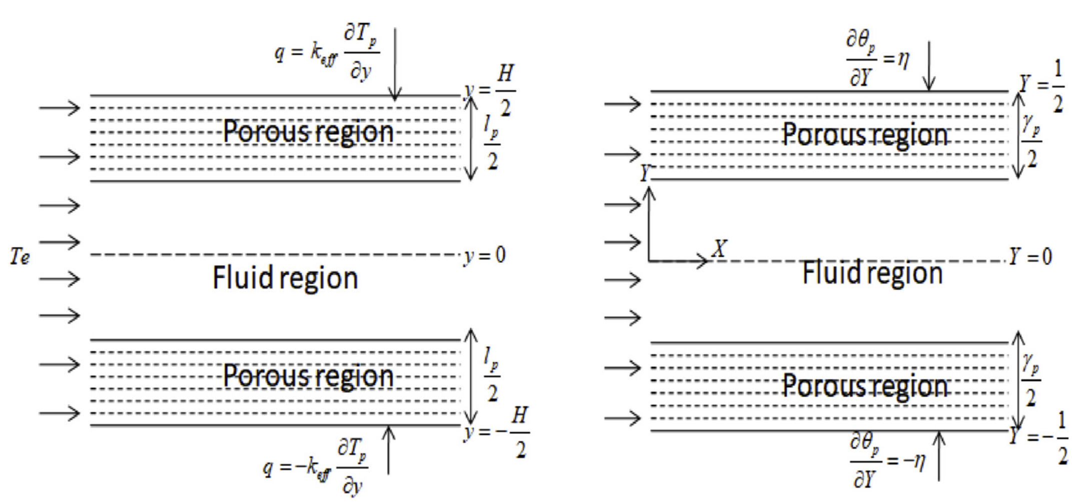
c	Constant less than unity
C_p	Specific heat, J/g °C
Da	Darcy number, $Da = K/H^2$
h_{px}	Local heat transfer coefficient, at the porous wall, W/m^2K
H	Width of the channel, m
K	Permeability, m^2
k_f	Thermal conductivity in fluid region, W/(m. K)
k_{eff}	Effective thermal conductivity in porous region, W/(m. K)
k_s	Thermal conductivity of the solid, W/(m. K)
l_p	Thickness of the porous region, m
MD	Number of divisions in the axial distance (X) direction
N	Grid number in the computational mess corresponding to non-dimensional normal coordinate Y
ND	Number of divisions in the normal(Y) direction
NP	Grid number at the porous-fluid interface
Nu_{px}	Local Nusselt number in porous region
P	Non-dimensional pressure
p	Pressure, kg $m^{-1}s^{-2}$
Pe	Peclet number, $Pe = U_{ref}H/\alpha_f$
P_{gr}	$P_{gr} = Re\frac{dp}{dx}$
q	Constant heat flux, W/m^2
Re	Reynolds number, $Re = \rho U_{ref}H/\mu_f$
T_b	Bulk mean temperature, K
T_f	Temperature in fluid region, K
T_p	Temperature in porous region, K
U_f	Non dimensional velocity in the fluid region
U_p	Non dimensional velocity in the porous region
T_i	Interfacial temperature, K
T_e	Inlet temperature, K
T_w	Wall temperature, K
u_f	Velocity in the fluid region, m/s
u_p	Velocity in the porous region, m/s
u_{ref}	Reference velocity, m/s
u_i	interfacial velocity at Porous - fluid, m/s
U_i	Non-dimensional interfacial velocity
x	Axial coordinate, m
X	Non-dimensional axial coordinate, x/H
X^*	Normalized non dimensional axial distance $= (X/Pe) = (x/PeH)$
y	Transverse coordinate, m
Y	Non-dimensional transverse coordinate, y/H

Greek symbols

α_{eff}	Thermal diffusivity in porous region, m^2/s
α_f	Thermal diffusivity in fluid region, m^2/s
η	α_f/α_{eff}
θ_f	Non-dimensional temperature in fluid region
θ_p	Non-dimensional temperature in porous region
θ^*	Non-dimensional bulk mean temperature, $\theta^* = (T_b - T_e)/(qH/k_f)$
θ_w	Non-dimensional wall temperature
$\tilde{\theta}_f$	Error in the energy equation in the fluid region
$\tilde{\theta}_p$	Error in the energy equation in the porous region
θ_i	Non-dimensional interfacial temperature
ε	μ_f/μ_{eff}
X^*_{fd}	Normalized fully developed length
γ_p	Porous fraction
μ_f	Viscosity in the fluid region, $(N.\ s)/m^2$
μ_{eff}	Effective viscosity in porous region, $(N.\ s)/m^2$
ρ	Fluid density, kg/m^3
φ	Porosity
ΔX^*	grid size in the flow direction $= 1/MD$
ΔY	grid size in the normal direction $= 1/ND$
ΔX^*_1	First non-uniform grid width defined by, $\Delta X^*_1 = c\ \Delta X^*$

layer approximation has not received much attention.

In view of the above, in this paper, the problem of forced convection in a channel partially filled with a porous medium subjected to constant wall heat flux has been studied. It is assumed that the flow is fully developed and the entrance effects are considered in the thermal field. Analytical expressions for momentum equations are available in Bhargavi and Sharath Kumar Reddy [25]. Numerical solutions using finite difference successive accelerated replacement (SAR) scheme (Satyamurty and Bhargavi [13] and Ramjee and Satyamurty [26]) have been obtained for energy equation in both the regions. The effects of important relevant parameters on temperature, bulk mean temperature and Nusselt number have been studied.



(a) Dimensional (b) Non Dimensional

Fig. 1. Physical model and coordinate system.