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Numerical investigation of pressure drop reduction without surrendering heat transfer enhancement in partially porous channel

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ABSTRACT

The present study is to investigate the numerical simulation of steady laminar forced convection in a partially porous channel, with four dissimilar porous-blocks, attached to the strip heat sources at the bottom wall. The analysis is based on the Navier–Stokes equation in the fluid field, the Darcy–Brinkman–Forchheimer flow model in the porous field, and the energy equations for two thermal fields. The effects of variations of different parameters such as porous blocks Darcy numbers, arrangements of dissimilar blocks, Forchheimer coefficient, Reynolds number, thermal conductivity and Prandtl number are investigated and the velocity and temperature fields are presented and discussed. In the dissimilar partially porous channel, it is found that when the blocks sorted from the lowest to the highest Da in the flow direction, the total heat transfer enhancement is almost the same as in the similar porous channel ($Nu/Nu_{\text{sim}} = 92\%$), while the total pressure drop is considerably lower ($P/P_{\text{sim}} = 28\%$). In addition, reverse arrangement of porous blocks is suggested to prepare more uniform temperature gradient in all heat sources.

1. Introduction

Thermal control of electronic equipment has become a major challenge in recent years due to the advancements in the design of modern high-speed components. Control of the component's temperature and temperature gradient are essential for the successful operation and reliability of the electronic products. In response to these demands, different techniques have been used in the past to obtain a well controlled thermal environment, including a variety of passive or active enhanced cooling techniques. One of the mentioned techniques is to apply porous material structures. Porous media can build up more fluid mixing and increase the surface area in contact with the coolant, that cause to augments the convective thermal transport.

Up to now numerous theoretical analyses and numerical simulations have been done on the convection heat transfer in fluid-saturated porous media. Among these studies, the heat transfer of a fully/partially porous channel with discrete heat source is of special interest due to its application for the cooling of electronics. For instance, Kaviany [1] used the Brinkman extended Darcy model to obtain a numerical solution of laminar flow in a porous channel bounded by isothermal parallel plate. Hadim [2] performed a numerical study to analyze forced convection in a channel fully or partially filled with the porous medium and containing discrete heat sources on the bottom wall. It was observed that the more does the Darcy number decrease, the more the heat transfer rate increases. Huang and Vafai [3] numerically investigated forced convection cooling in an isothermal parallel plate channel. Chen and Hadim [4] numerically studied laminar forced flow in a porous channel filled with fibrous medium saturated with a power-law fluid. According to the result in the non-Darcy regime with decrease of power law index, the thermal boundary layer thickness decreases significantly. Consequently, the fully developed Nusselt number increased considerably in the non-Darcy regime. Yan and Jen [5] investigated developing fluid flow and heat transfer in a channel partially filled with porous medium. The Nusselt number and friction factor were presented as a function of axial position, and the effects of the size of porous blocks were analyzed.

Although using the porous structures increase heat transfer rate, in hydrodynamic consideration, this method imposes higher pressure drops in porous field. To reduce the pressure drop without surrendering heat transfer enhancement, two possible techniques are effective; first using porous media in partly filled arrangement and second by varying the structural properties such as permeability. The related characteristics study, on partly filled channels and variable permeability, can be found in N.J. Rabadi [6], T.V.

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Nomenclature

BDa	Base Darcy number
c	specific heat (J kg^{-1} K^{-1})
C	inertia coefficient
Da	Darcy number (K/R^2)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
K	permeability of the porous medium (m^2)
l_i	length of channel upstream from the porous-block array (m)
l_o	length of channel downstream from the porous-block array (m)
l_T	length of the channel (m)
Nu	Nusselt number, $Nu = qR/(T_w - T_i)k_f$
P	dimensionless pressure, $pH/\mu U_{av}$
Pr	Prandtl number, ν/a
q	uniform heat flux from each heat source, (W m^{-2})
R	channel height (m)
Re	Reynold number, U_0H/ν
R_C	Forchheimer coefficient ratio, C_{i+1}/C_i
R_{Da}	Darcy ratio, Da_{i+1}/Da_i
R_k	thermal conductivity ratio, k_{eff}/k_f
S	spacing between heat sources (m)
T	temperature (K)
u	*x*-component velocity (ms^{-1})
v	y-component velocity (ms^{-1})
V	velocity vector (ms^{-1})
W	width of heat source (m)
X	horizontal coordinate (m)
y	vertical coordinate (m)

Greek symbols

α	thermal diffusivity (m^{2}s)
γ	binary parameter defined in Eqs. (2)–(5)–(7)
ε	porosity of the porous medium
Θ	dimensionless temperature, $(T - T_i)/(qH/k_f)$
μ	dynamic viscosity (kg m^{-1} s^{-1})
ν	kinematic viscosity (m^2 s^{-1})
φ	stream function (m^2 s^{-1})

Subscripts

av	average
eff	effective
f	fluid
i	inlet condition
m	overall mean
s	solid
sim	similar
T	total

Morosuk [7], Ould-Amer et al. [8], Prasad and Simmons [9], S.Y. Kim and A.V. Kuznetsov [10] and C.T. Simmons [11].

A.V. Kuznetsov [12] analytically investigated fully developed forced convection in a parallel-plate channel partly filled with a homogeneous porous material. His new analytical solution made it possible to extensively investigate possibilities of enhanced heat transfer by changing values of pertinent parameters.

D.C. Chandrasekhara [13] considered a sloped vertical surface saturated with varying permeability porous medium and obtained a significantly altered in local velocity field for combined free and forced convection. Nield and Kuznetsov [14] studied forced convection in a channel with asymmetric heating and asymmetric permeability and thermal conductivity varying across the channel. Nield,et al. [15], used analytical solutions to investigate the effect of variable permeability of porous media on the *Nu* number. They found that the increase in the *Nu* is due to the variation in transverse permeability. A. V. Kuznetsov [16] analytically investigated effects of thermal dispersion on forced convection in a parallel-plate channel partly filled with a Brinkman–Forchheimer porous medium. He was established, that the curves depicting the dependence of the Nusselt number on the particle Reynolds number delimit three regions. This study is to investigate the effect of the application of both the partly filled arrangement and varying permeability on the heat transfer enhancement and the pressure drop reduction.

A numerical investigation is performed on the hydrodynamic and heat transfer characteristics of four sequential heat sources mounted with different permeability porous structure. Furthermore, the influences of various thermal characteristics are determined. Also, the heat transfer variation and pressure drop reduction in a dissimilar partially porous channel are evaluated, and the results are compared with those of the similar partially porous channel case. It is shown that using these two techniques together can exert a significant influence in the reducing of the pressure drop without surrendering the heat transfer augmentation along the channel.

2. Mathematical formulation

A schematic of the partially porous channel with four discrete heat sources and coordinate system is shown in Fig. 1(a). The porous layers are located above the heat sources and anywhere else is nonporous. The channel height and total length are denoted by *R* and l_T, respectively; also both channel walls are insulated except in heat source sections on lower wall. Each heat source dissipates an equal and uniform heat flux q over its length *W*. The fluid enters the channel at uniform temperature T_i with a parabolic velocity profile. The flow is supposed to be single phase, steady, laminar, incompressible, and two dimensional. The thermo-physical properties of the fluid and the effective properties of the solid matrix are assumed to be constant. The porous medium is considered to be homogeneous, isotropic, non-deformable, saturated with fluid and in local thermal equilibrium with the fluid. To neglect the channeling effect, fibrous media are considered which have a relatively constant porosity and permeability even close to the walls [17]. Also the effects of thermal dispersion, natural convection and thermal radiation are neglected. According to Lundgren [18], the effective viscosity of porous medium can be considered equal to that of the fluid in higher porosities. For the partially porous channel case, instead of solving the two sets of describing equations separately, the equations can be combined into one set by introducing the binary parameter γ, where γ is either zero or one for fluid and porous reigns respectively. The general forms of mass, momentum and energy balance governing equations, used in this study are [2]:

$$\nabla \cdot \boldsymbol{V} = 0 \tag{1}$$

$$\frac{\rho}{\varepsilon^2}(\boldsymbol{V}\cdot\nabla)\boldsymbol{V} = -\nabla p + \rho g - \gamma\left[\frac{\mu}{K} + \frac{\rho C}{\sqrt{K}}|\boldsymbol{V}|\right]\boldsymbol{V} + \mu'\nabla^2\boldsymbol{V} \tag{2}$$

$$(\rho C)_f(V\cdot\nabla T) = K\nabla^2 T \tag{3}$$