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Analysis of fluid flow and heat transfer in a channel with staggered porous blocks

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ABSTRACT

Fluid flow and heat transfer characteristics in a channel with staggered porous blocks were numerically studied in this paper. The Navier–Stokes and Brinkman–Forchheimer equations were used to model the fluid flow in the open and porous regions, respectively. Coupling of the pressure and velocity fields was resolved using the SIMPLER algorithm. The local thermal equilibrium model was adopted in the energy equation to evaluate the solid and fluid temperatures. The effect of Darcy number, Reynolds number, porous block height and width on the velocity field were studied. In addition, the effects of the above parameters as well as the thermal conductivity ratio between the porous blocks and the fluid on the local heat transfer were analyzed. The pressure drops across the channel for different cases were discussed. The results show that the flow behavior and its associated local heat transfer are sensitive to the variation of the above parameters. It is predicted by the present study that an increase in the thermal conductivity ratio between the porous blocks and the fluid results in significant enhancement of heat transfer at the locations of the porous blocks.

1. Introduction

The investigation of forced convection heat transfer in a channel filled with porous media is of practical interest in the industry. It has been demonstrated that heat sinks made of porous media with high thermal conductivity and large surface area improve heat transfer performance and thus are widely used in various industry applications such as heat exchangers, chemical reactors and heat pipes [1–4]. The fundamentals of heat transfer in porous media have been studied extensively in the past decades [5–8]. Recent investigations of heat transfer in porous media with spherical open cell microstructure such as metal and graphite foams indicate that such materials offer more promising prospects for use in heat sinks [9–14].

A channel can either be partially or fully filled with a porous medium. In the fully filled case, the channel would be completely occupied by the porous medium. If it were to be partially filled, the channel would usually be inserted with porous layers [Fig. 1(a)] or discrete porous blocks [Fig. 1(b)]. Many experimental and numerical studies have been performed to investigate the transport phenomena in channels fully filled with a porous medium [9,15]. However, it was reported that substantially high pressure drop will occur in these channels [11,16] while those partially filled with porous media have much lower pressure drops [11,16,17]. Studies of channels partially filled with porous media [16,18–20] showed that it may not be necessary to completely fill the channel with the porous medium to derive the maximum heat transfer. Fu et al. [21] and Zhang and Zhao [22] numerically studied the convection heat transfer in a channel with a single porous block mounted on the heated wall. In the work of Fu et al. [21], various parameters including the geometry of the porous block and Reynolds number were studied. Their results showed that heat transfer was enhanced by using a porous material with higher porosity and particle diameter and with a height of the porous block which is half that of the channel. Zhang and Zhao [22] also showed that heat transfer is significantly enhanced in the channel with single porous block.

Many studies have been reported on the channel with multiple porous blocks arranged on one side of the wall [23–26]. Among them, the pioneer study involving a channel with multiple porous blocks attached on the external surface of a plate was carried out by Huang and Vafai [23]. Their results showed that the presence of porous blocks significantly changes the characteristics of fluid flow and heat transfer. A detailed study of forced convection enhancement in a channel with multiple porous blocks arranged on the bottom wall was reported by Huang and Vafai [24]. The stream function-vorticity method was adopted to simulate the fluid flow in the composite geometry. The effects of various parameters such as Darcy number, Reynolds number, Prandtl number on the flow field and heat transfer were investigated. Their results showed that the local heat transfer was closely related to the velocity field. The vortices that occurred in the flow field have significant effects on

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Nomenclature

a	porous block height (m)
b	space between consecutive porous blocks (m)
C_E	inertial coefficient of porous media
C_{pf}	specific heat of fluid (J/kg K)
Da	Darcy number based on channel height
H	channel height (m)
K	permeability of the porous medium (m^2)
k_{eff}	effective thermal conductivity (W/m K)
k_f	thermal conductivity of fluid (W/m K)
l	length (m)
L	length of the computational domain (m)
Nu_x	local Nusselt number
p	pressure (Pa)
p^*	dimensionless pressure drop
Re	Reynolds number
S	source term
T	temperature (°C)
u	velocity component in the x-direction (m/s)
V	volume (m^3)
$\mathbf{V}$	velocity vector (m/s)
w	porous block width (m)
x, y	coordinates

Greek symbols

ρ	density (kg/m^3)
ε	porosity
μ	dynamic viscosity (kg/m s)
φ	average quantity
ϕ	dependent variable
Γ	diffusion coefficient
Λ_H	inertial parameter

Subscripts

f	fluid phase
in	inlet
i, j	direction of component
s	solid phase
w	wall

the heat transfer characteristics. A comparison between the channels with and without porous blocks showed that substantial heat transfer enhancement can be achieved by the insertion of porous blocks. Targui and Kahalerras [27] numerically investigated two configurations of channels with porous blocks inserted in the annular gap of a double pipe heat exchanger. One configuration had the porous blocks arranged on the inner cylinder, while the other had porous blocks on both cylinders in a staggered manner. Their results showed that better heat transfer can be obtained in the structure with staggered porous blocks, albeit, with a more distorted flow field and higher pressure drop. Hwang [28] conducted an experimental study of fluid flow and heat transfer in a channel with porous blocks arranged on both the upper and bottom walls. The porous blocks were fixed in a staggered manner. Their results showed that better heat transfer was obtained under constant pumping power using staggered porous blocks instead of staggered solid blocks. A similar experimental study was performed by Ko and Anand [29] using metal foams as heat sinks. Their results showed that heat transfer in staggered porous metal foam blocks can be enhanced by as much as three times that of an open channel. Miranda and Anand [30] numerically studied the fluid flow and heat transfer in a channel with staggered porous blocks with constant heat flux imposed on both walls. Different parameters were investigated for the configuration. It was shown that the flow fields have distinct features by altering the parametric values and the average heat transfer can be enhanced by a careful selection of the operating condition.

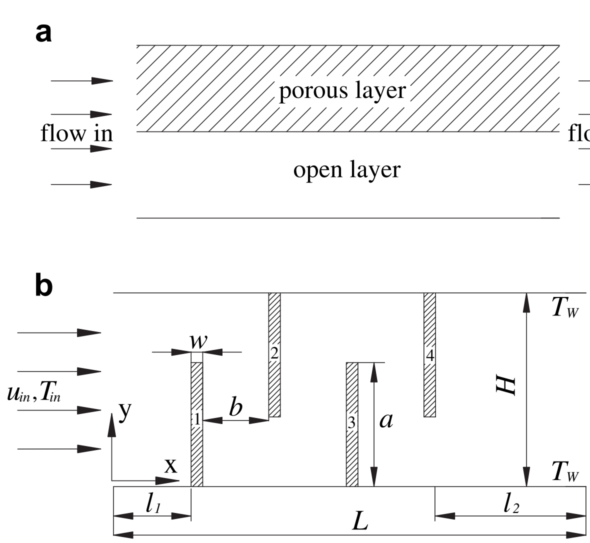

Fig. 1. Schematic diagram of the parallel plate channel with (a) porous and open layers (b) staggered porous blocks.

From the above literature review, it is clear that fluid flow in the channel with staggered porous blocks is rather complex and that heat transfer is significantly affected by the flow field. The objective of this paper is to numerically study the laminar fluid flow and local heat transfer in channels with staggered porous blocks. The present work is different from the published work of Huang and Vafai [23,24] in which the porous blocks are arranged only on one sidewall of the channel. The present paper is essentially different from that of Miranda and Anand [30] not only in terms of the configurations that were studied. The constant wall temperature boundary condition was studied in the present work, whereas constant heat flux was assumed on the two walls in the work of Miranda and Anand [30]. For thermal management applications, the convection heat transfer would be affected by the arrangement of porous blocks. The alternately installed porous blocks in this study may cause local hot spots where high local temperatures could damage the electronic devices. Therefore, the present work would focus on these aspects. The work of Miranda and Anand [30] focused mainly on the average Nusselt number in the channel. To the best knowledge of the authors, the local Nusselt number in the staggered porous blocks has not been investigated.

2. Mathematical formulations

2.1. Problem description

The present work studied the fluid flow and heat transfer between two parallel plates with staggered porous blocks on both the upper and lower walls. The schematic domain of the current problem is shown in Fig. 1(b). The two walls of the channel are heated to a temperature of T_w. As the fluid at lower temperature T_{in} flows into the channel in which the temperatures of two walls are higher, convection heat transfer occurs between the walls and the