Alexandria Engineering Journal (2015) **54**, 853–869

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Alexandria Engineering Journal

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ORIGINAL ARTICLE

Modeling mixing convection analysis of discrete partially filled porous channel for optimum design

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Received 24 May 2015; revised 27 June 2015; accepted 4 July 2015
Available online 14 August 2015

KEYWORDS

Mixing convection;
Heat transfer;
Prandtl number;
Nusselt number;
Darcy number;
Richardson number

Abstract Mixing convection flow inside a convergent horizontal channel partially filled with porous material and a clear channel are investigated numerically in the present study. Four discrete heat sources with uniform heat flux have been applied on the bottom surface of the channel. Three different channel exit heights are studied (H_e = 1, 0.5 and 0.25). The thermal and flow-field analysis inside the channel is investigated for different wide range of Reynolds number ($50 \leqslant Re \leqslant 300$), Darcy number ($10^{-2} \leqslant Da \leqslant 10^{-6}$), Richardson number ($0 \leqslant Ri \leqslant 100$) and Prandtl number ($0.7 \leqslant Pr \leqslant 10$). The present study carried out the effect of the channel exit height, Richardson number, Reynolds number, Darcy number and Prandtl number on the flow-field, the Nusselt number and the overall heat transfer performance. The Brinkman–Forchheimer–extended Darcy model is used to solve the governing equations of the fluid in the porous medium. The results reveal that the boundary layer thickness and flow velocity increase at high Richardson number for both porous and clear channels. The overall Nusselt number increases significantly for further increase in Darcy number, particularly for $Ri > 10$. The smallest channel exit height ($H_e = 0.25$) provides a high Nusselt number and low overall heat transfer performances. Furthermore, Richardson number has a small significant effect on overall Nusselt number and heat transfer performance at low Prandtl number.

1. Introduction

Enhancement heat transfer is vital in many thermal industrial applications such as; electrical machines cooling, macro and microelectronic equipments, refrigeration and air-conditioning, and gas flow heating in manufacturing and waste-heat recovery. In addition, it is required to increase the heat transfer rate in air and liquid cooling of engine and turbomachinery systems, sensible heating and cooling of viscous medium in thermal processing of chemical, pharmaceutical, and agricultural products. Therefore, improving the heat exchange performance increases significantly the thermal efficiency as well as the economics of the design and operation process. In order to enhance the heat transfer techniques, the thermal resistance in a conventional heat exchanger is reduced by promoting high convective heat transfer coefficient with or without increasing surface area. As a result, the heat exchanger size and the pumping power can be reduced. In addition, the

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Peer review under responsibility of Faculty of Engineering, Alexandria University.

http://dx.doi.org/10.1016/j.aej.2015.07.006
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Nomenclature

C	inertial coefficient
C_p	specific heat at constant pressure (J/kg K)
Da	Darcy number
F	factor
Gr	Grashof number
H	inlet channel height (m)
h	heat transfer coefficient (W/m^2 K)
h_e	exit channel height (m)
H_e	dimensionless exit channel height (h_e/H)
H_p	dimensionless porous height (h_p/H)
h_p	porous height (m)
H_x	dimensionless local channel height (h_x/H)
h_x	local channel height (m)
K	permeability of the porous medium (m^2)
k_{eff}	effective thermal conductivity of the fluid-saturated porous medium (W/m K)
k_f	thermal conductivity of the fluid (W/m K)
Kr	thermal conductivity ratio (k_{eff}/k_f)
l	channel length (m)
L_I	dimensionless upstream unheated distance (l_i/H)
L_s	dimensionless distance between porous blocks (l_s/H)
l_s	distance between heat source (m)
N	total number of heat sources
Nu	Nusselt number
p	pressure (Pa)
P^*	pressure dimensionless
P_i	inlet pressure (Pa)
Pr	Prandtl number
q	uniform heat flux (W/m^2)
Ra	Rayleigh number
Re	Reynolds number
Ri	Richardson number
T	temperature (K)
u	main stream velocity (m/s)
U^*	dimensionless main stream velocity (u/u_i)
v	transverse velocity (m/s)
V^*	dimensionless transverse velocity (v/u_i)
w_p	porous block width (m)
W_p	dimensionless porous blocks width (w_p/H)
x, y	coordinates
X, Y	dimensionless coordinates (x/H, y/H)
X_{sn}	dimensionless heat sources centerlines (x_{sn}/H)

Greek symbols

Δ	difference between inlet and exit
α	thermal diffusivity of the fluid (m^2/s)
β	thermal expansion coefficient (K^{-1})
ε	porosity
θ	dimensionless temperature, $k_f(T - T_i)/qH$
θ_m	bulk temperature
θ_w	wall temperature, $k_f(T_w - T_i)/qH$
μ	dynamic viscosity (kg/m s)
μ_{eff}	effective dynamic viscosity (kg/m s)
μr	viscosity ratio
ν	kinematic viscosity (m^2/s)
ξ	overall heat transfer performance parameter
ρ	density (kg/m^3)

Subscripts

av	average
e	exit
eff	effective
f	fluid
i	inlet
m	bulk
p	porous
r	ratio
sn	heat source number (1, 2, 3 and 4)
w	wall
x	local

operating temperature of the heat exchanger can be decreased as well as increasing the heat duty of an existing exchanger.

The heat exchanger enhancement can be classified into passive and active techniques. The active technique required direct external power such as; surface and fluid vibrations, mechanical aids, injection, suction, jet impingement and electrostatic fields, while the passive technique required geometry modifications such as; rough, extended and treated the surfaces, swirl flow, surface tension devices, coiled tubes, and additives for liquid and gases.

Porous medium and transport are becoming vital in heat exchanger design in order to minimize the heat exchanger size with lower Reynolds number for small-scale applications such as electronic devices cooling. Huang and Vafai [1] studied the effect of porous block array on flow field and thermal characteristics of external laminar forced convection flow. They concluded that the presence of a porous block array near the boundary had significantly affected the convection characteristics. Hadim [2] studied numerically the effect of partially and fully filled porous channels using discrete heat source on the bottom wall. He reported that the enhancement in heat transfer is the same for the two cases when the width of the heat source is equal to the spacing between the porous layers for partially filled porous channel, whereas the partially filled porous channel provided low pressure drop (Δp) compared to fully filled channel. Sung et al. [3] studied numerically flow and heat transfer characteristics of forced convection in a channel which was partially filled with porous medium using Brinkman–Forchheimer–extended Darcy model. They reported that for fixed Darcy number (Da), the heat transfer enhanced as the thermal conductivity ratio (kr) increased. Also, the flow rate increased as porous block height (H_p) and Darcy number decreased. Moreover, the pressure drop increased as the porous block height increased and Darcy number decreased. In addition, Akam et al. [4] used Darcy–Brinkman–Forchheimer model to investigate transient forced convection in the developing region of parallel plate for a high thermal conductivity porous substrate. Their results showed that the highest Nusselt number (Nu) was achieved for fully porous duct. Furthermore, they observed that decreasing