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Combined effects of corrugated walls and porous inserts on performance improvement in a heat exchanger channel

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ABSTRACT

In this paper, a numerical study is performed to investigate the combined effects of corrugated walls and porous inserts on heat transfer enhancement and thermal-hydraulic performance in a channel. Accordingly, a sinusoidal wavy wall channel partially filled with a porous material placed at its core is considered. The Darcy-Brinkman-Forchheimehr model is considered to study the flow in porous region and finite volume method (FVM) with SIMPLE algorithm are applied to solve the governing equations. It was found that the amplitude of the wavy wall has a considerable effect on average Nusselt number especially at small Darcy numbers. For example, at Re $= 300$, $\delta = 0.3$, $\alpha = 0.2$ and $Da = 10^{-2}$ the average Nusselt number of wavy channel increases about 12% in comparison with the straight one, while it improves about 38% at $Da = 10^{-4}$. Moreover, there is an optimum value of Darcy number corresponding to maximum performance evaluation criteria (PEC). At $\delta = 0.3$ and $Re = 300$, for straight channel and wavy channel with $\alpha = 0.1$ the optimum value of Darcy number occurs at $Da = 10^{-3}$, while for $\alpha = 0.2$ and 0.3 the $Da = 10^{-4}$ leads to the maximum PEC.

1. Introduction

Heat transfer improvement in channels is one of the most noteworthy topics for researchers due to the numerous engineering applications such as heat exchangers, solar collectors, electronic cooling devices, etc. Different passive techniques have been developed to achieve this goal [1]. Installing fins [2] and twisted tapes [3], and addition of nanoparticles [4] are some examples of these techniques. Using corrugated (or wavy) walls and porous material inserts are two low cost and effective methods to enhance the heat transfer rate. The usage of porous materials in energy related systems has been the topic of many researches in recent years. However, it is recommended to partially fill the channel and pipes with a porous medium as these materials create a high value of pressure drop [5,6]. Utilizing porous medium in heat exchangers improves the rate of heat transfer through three mechanisms including flow redistribution, increase in effective thermal conductivity and improving the radiative heat transfer [6]. For channels and tubes partially filled with a porous medium located at the core, the main effect of the porous medium is forcing the flow to accelerate in the outer region (near the walls) depending on the permeability of the porous medium which decreases the thermal boundary layer thickness and consequently increases the convective heat transfer [6]. Moreover, using wavy walls in a thermal system such as heat exchanger causes a better mixing of the fluid, which increases the heat transfer rate [7].

Rush et al. [8] experimentally studied the flow behavior and heat transfer of laminar and transitional flows in sinusoidal wavy passages. They found that the location of the onset of mixing is related to the Reynolds number and channel geometry. Wang and Chen [9] numerically investigated the forced convection heat transfer in a wavy channel. They studied the effects of different parameters containing wavy geometry and Reynolds number on the Nusselt number and the skin-fraction coefficient. They concluded that the heat transfer improvement is not considerable at smaller values of amplitude wavelength ratio. However, there is a significant enhancement in heat transfer rate for larger values of amplitude wavelength ratio, especially for higher Reynolds numbers. Bahaidarah et al. [10] performed a numerical study on heat and momentum transfers of a fluid with Prandtle number of 0.7 through a periodic wavy passage. Two different configurations including sinusoidal and arc-shaped profiles were considered in their paper. They observed that at low Reynolds numbers, a small part of the channel is covered by recirculation flow, while the concave area of the channel is completely covered by recirculation flow at higher Reynolds numbers. Yin et al. [11] carried out a numerical study on fluid flow and heat transfer in corrugated channels with different phase shifts between the upper and lower sinusoidal walls. The Reynolds numbers were considered in the range of 2000–10000. It was found that the Nusselt number and friction factor reduce with an

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Nomenclature

a	Wave amplitude (m)
C_F	Forchheimer coefficient (−)
C_p	specific heat at constant pressure ($J\ kg^{-1}K^{-1}$)
Da	Darcy number (−)
f	friction factor (−)
h	convective heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
H	average distance between corrugated walls (m)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
K	permeability of porous material (m^2)
L	channel length (m)
L_w	wavelength of the corrugated walls (m)
Nu	Nusselt number (−)
p	pressure (Pa)
P	Non-dimensional pressure
PEC	Performance Evaluatuion Criteria
R_k	Thermal conductivity ratio (−)
Re	Reynolds number (−)
S	porous layer thickness (m)
T	temperature (K)
u, v	velocity components in x and y directions, respectively (ms^{-1})
U, V	Non-dimensional velocity components (−)
U_{in}	inlet velocity (ms^{-1})
x, y	rectangular coordinates components (m)
X, Y	Non-dimensional rectangular coordinates components (−)

Greek symbols

α	Non-dimensional wave amplitude (−) $\left(\alpha = \frac{a}{H}\right)$
ε	Porosity (−)
δ	Non-dimensional porous layer thickness (−) $\left(\delta = \frac{S}{H}\right)$
μ	dynamic viscosity ($kg\ m^{-1}s^{-1}$)
ν	kinematic viscosity (m^2s^{-1})
θ	dimensionless temperature (−)
ρ	fluid density ($kg\ m^{-3}$)

Subscripts/superscripts

ave	average value
in	inlet
w	wall
x	Local value

increase in phase shift. A numerical study on fully developed flow and heat transfer in three different corrugated channels including sinusoidal, triangular, and arc-shaped channels was performed by Ramgadia and Saha [12] for a fixed Reynolds number (Re = 600). They concluded that the channels with arc-shaped, sinusoidal and triangular walls have the maximum values of heat transfer rate and pressure drop, respectively. From the viewpoint of thermal performance, the sinusoidal, arc-shaped and triangular profiles have the maximum thermal performance factor respectively. Mills et al. [13] numerically studied the heat transfer and thermal-hydraulic performance of a sinusoidal wall channel using Lattice-Boltzmann method. They concluded that using wavy wall channels with small amplitudes is preferable for heat exchanger applications with large flow rate. Some researchers simultaneously employed wavy walls and nanoparticles to improve the heat transfer rate in channels [14–17].

Many research investigations have been carried out on fluid flow and forced convection heat transfer in channels partially filled with porous media. Poulikakos and Kazmierczak [18] performed a theoretical study on fully developed forced convection heat transfer in the channel with two different configurations containing parallel plates and circular pipe partially filled with porous matrix. In their study, the porous matrix was attached to the channel walls. They considered both constant heat flux and constant wall temperature as thermal boundary conditions. Vafai and Kim [19] presented an exact solution to study the fluid mechanics at the interface region between fluid and porous zones. A comprehensive analysis on different types of hydrodynamic and thermal conditions between a fluid layer and porous medium was carried out by Alazmi and Vafai [20]. Mohammad [6] numerically investigated the heat transfer enhancement and the pressure drop in pipes and channels which are fully and partially filled with porous material. He concluded that there is a lower value of pressure drop for a partially filled channel in comparison with fully filled one. Alkam et al. [21] numerically studied transient forced convection heat transfer in the developing region of a channel partially filled with a porous substrate. The results show that hydrodynamic and thermal characteristics of the flow in the developing region are more affected by Darcy number and the microscopic inertial coefficient when compared with the fully developed one. Jen and Yan [22] studied the flow and heat transfer in a three-dimensional channel partially filled with porous medium. They found that as the porous ratio increases, the Nusselt number and friction factor increase. Shokuhmand et al. [23] investigated the effect of porous layer location on heat transfer improvement of fully developed laminar flow in a channel. They used Lattice Boltzmann method in their simulation and found that for high values of thermal conductivity and Darcy number, it is better to locate the porous layer at the walls of the channel. Yang et al. [24] performed a theoretical analysis to study the heat transfer in a tube partially filled with porous material. They concluded that for lower values of pumping power, higher thermal

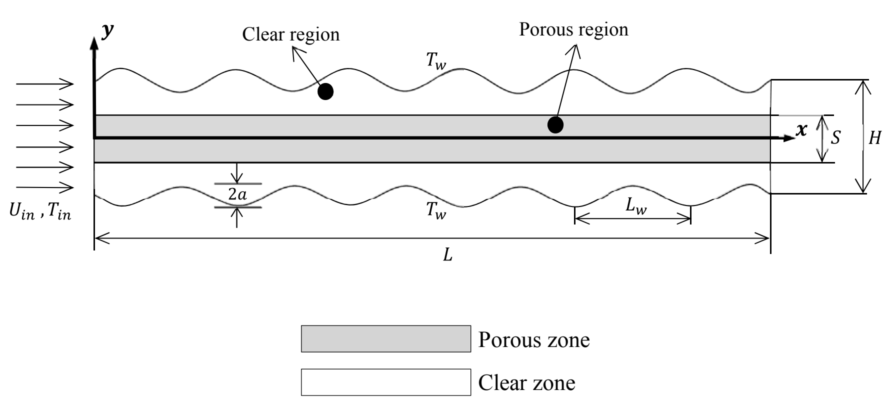

Fig. 1. Schematic diagram of the problem.