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Thermal and hydraulic performances of a tube filled with various thermal conductivities of porous media

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ABSTRACT

The present study aims to numerically investigate the influence of thermal conductivity of a porous medium (k_s) on the Nusselt (Nu) and performance evaluation criteria (PEC) numbers of an enhanced tube for heat exchanger (ETfHE). This is accomplished with a porous medium partially inserted within the core flow of the tube under fully developed laminar flow for heat exchange. In this research we demonstrated four cases: two with air as the working fluid, one with water, and one with an assumed fluid whose density is a quarter of that of water while the other physical parameters remain the same. The packing ratio of the porous medium is 90%, the scope of *Re* is 25–2000, and the thermal conductivity of the porous medium ranges from 0.1 to 200 W/(m K). The simulation results show that, under the given working conditions, the Nu and PEC numbers of the ETfHE will neither increase monotonically with the thermal conductivity of the porous medium nor increase monotonically with the Reynolds (*Re*) number. These results are different from the conventional thinking that increasing the thermal conductivity of a porous medium will increase the overall performance of the ETfHE.

1. Introduction

The utilization of heat transfer enhancement technologies is drawing increasing attention today due to worldwide energy crisis. Presently, enhancing convective heat transfer and reducing flow resistance have been the two most effective ways to improve the performance of heat exchangers [1]. The most frequently applied methods for single-phase convective heat transfer enhancement include the reduction of boundary layer thickness, the increase of the surface area of the tube wall by installing fins, and the increase of fluid velocity from laminar flow to turbulent flow. Although the heat transfer enhancement technology has grown to the fourth generation [2], the aim of these techniques is to decrease the thickness of the velocity boundary layer by either changing the shape and area of the tube wall or changing the fluid flow direction, to decrease the thermal boundary layer. These techniques can be classified as boundary flow heat transfer enhancement.

One method to enhance heat transfer for fluid flowing over a flat plate is to increase fluid velocity to form larger velocity and temperature gradients near the wall. While the increase of fluid velocity has no influence on the *Nu* number under either constant heat flux or temperature boundary conditions; employing continuous expansion surface area for fully developed laminar inner-tube flow will generate significant friction loss. This also causes considerable momentum dissipation. As a result of the application of boundary flow heat transfer enhancement, the flow resistance will experience a considerable increase. If this increase is excessive, it will even limit the application scope of this kind of heat exchangers.

Bejan [3] divided the flow at the entrance of a tube into boundary flow and core flow. Boundary flow has a relatively higher velocity and temperature gradient, while core flow has a more homogeneous velocity and temperature profile. Based upon this, Liu et al. [4] proposed the concept of core flow heat transfer enhancement aiming to improve the performance of fully developed laminar tube flow. The authors found that the velocity profiles in a fully developed laminar tube flow can be changed in a similar way to those in the entrance of the tube. Their work shows that this idea can effectively improve the performance of both flow and heat transfer within the fully developed laminar tube flow [5,6]. They also conducted a series of theoretical analysis on the relationship among the velocity vectors, temperature gradient, and pressure gradient. This was to improve the total performance of tubes by enhancing heat transfer without significantly increasing the pressure drop [7–9].

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Nomenclature

C_F	dimensionless resistant coefficient inside the porous medium (–)
c_p	specific heat capacity at constant pressure (J/(kg K))
d	tube diameter (m)
f	flow resistance coefficient (–)
h	heat transfer coefficient (J/(m^2 K))
k	thermal conductivity (J/(m K))
K_p	permeability of the porous medium (–)
L	tube length (m)
Nu	Nusselt number (–)
p	fluid pressure (pa)
Pr	Prandtl number (–)
PEC	performance evaluation criteria (–)
Re	Reynolds number (–)
Q	heat exchange between tube wall and fluid (W)
T	temperature (K)
u	velocity in x direction (m/s)
v	velocity in y direction (m/s)
V	average velocity across the tube (m/s)
x, r	coordinates in x, r directions (m)
ΔP	pressure drop (pa)
pe	Peclet number (–)
PEC	performance evaluation criteria (–)

Greek symbols

ρ	fluid density (kg/m^3)
í	kinematic viscosity (m^2/s)
β	thermal expansion coefficient (1/K)
ε	porosity (–)
a	thermal diffusivity (m^2/s)
Ω	shape factor (–)

Subscripts

s	parameter of solid matrix
a	fluid parameter
m	average parameter of the porous medium zone
w	tube wall
f	fluid in the tube
0	smooth tube

Several researchers have shown their interests in heat transfer enhancement by inserting a porous medium into the tube/channel to improve its overall performance. For instance, Tong et al. [10] conducted an analysis on the heat transfer performance of a channel inserted with a porous medium. The results indicated that heat transfer enhancement could be obtained. Huang and Vafai [11] built a vorticity stream function formulation and the analytical results further confirmed that a significant heat transfer increase could be obtained by adding porous blocks on the bottom wall of an isothermal parallel-plate channel. Chikh et al. [12] focused their attention on an annular cylindrical duct with a porous substrate mounted on the inner cylinder. The velocity field was obtained analytically for a fully developed flow. The results showed that there exists a critical thickness of the porous layer at which heat transfer is minimal. Sung et al. [13] reported some results on the effect of both height and permeability of a single porous block on the flow and heat transfer characteristics of forced convection in a channel. Mohamad and Pavel [14,15] carried out numerical simulations and experimental verifications on the fluid flow and heat transfer performances of an inner tube filled with a porous medium. Their results revealed that the heat transfer was considerably enhanced. Yan and Jen [16] investigated the development of fluid flow and heat transfer in a channel partially filled with a porous medium. The *Nu* number and friction factor, *f*, were presented as a function of axial position and the effect of the size of the porous blocks was analyzed. Kuznetsov [17] 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. Nield and Kuznetsov [18] studied forced convection in a channel with asymmetric heat, permeability, and thermal conductivity. Zehforoosh and Hossainpour [19] conducted a numerical investigation of steady, laminar forced convection in a partially porous channel. The effects of different parameters such as Darcy numbers, arrangements of dissimilar blocks, Forchheimer coefficient, *Re* number, thermal conductivity, and Prandtl number were investigated and the velocity and temperature fields are presented and discussed. Nebbali and Bouhadef [20] performed a numerical investigation for heat transfer enhancement in a parallel-plate channel partially inserted with porous blocks. The modified Brinkman–Forchheimer extended Darcy model for power-law fluids was used in the porous layer with the Navier–Stokes equation being employed in the clear region of the channel. Li et al. [21] numerically studied the convective heat transfer in a channel with staggered porous blocks. The effects of Darcy number, *Re* number, porous block height, and width on the thermohydraulic performance were analyzed. Aguilar-Madera et al. [22] solved the effective-medium equations for modeling momentum and heat transfer in a parallel-plate channel with a partially porous insert. The solution of the momentum-transport problem was carried out using implicit integral equation formulations based on Green's functions, whereas the heat transfer problem was solved numerically using the finite element method. Pathak and Ghiaasiaan [23] conducted a numerical simulation on the solid–fluid heat transfer and thermal dispersion during laminar pulsating flow through porous blocks, and have conducted a two-dimensional simulation in porous medium composed of periodically arrays of square cylinders with a CFD tool, with sinusoidal time variation of flow as the inlet boundary condition.

A number of authors have studied variations of the thermal conductivity of porous media. Munagavalasa and Pillai [24] evaluated the dependency of the thermal conductivity of a dual-scale porous medium on the péclet number at different interfacial volume and heat transfer rates using a finite-element simulation for a steady-Newtonian flow. It was shown that effective thermal conductivity is strongly correlated to the péclet number. The effective thermal conductivity and permeability of bisized porous media is experimentally studied by Dias et al. [25]. They found that bisized porous media have a higher effective thermal conductivity in comparison with mono-sized porous media and, as a result, thermal performance is improved by using the bisized porous media. In the other work, Pedras and Lemos [26] studied thermal dispersion components of a periodic porous medium. An infinite array of longitudinal displacement of elliptic rods is used as a numerical model with Dirichlet and heat flux boundary conditions being imposed on the porous medium. Their results indicated that the transversal thermal dispersion coefficient component shows great sensitivity on porosity, boundary condition types, medium morphology, and solid–liquid conductivity ratios; whereas the longitudinal component is not sensitive to the aforementioned parameters. Yang and Nakayama [27] investigated static thermal conductivity and