Applied Thermal Engineering 109 (2016) 761–774

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Enhancement of heat transfer and heat exchanger effectiveness in a double pipe heat exchanger filled with porous media: Numerical simulation and sensitivity analysis of turbulent fluid flow

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HIGHLIGHTS

- Turbulent heat transfer in a double pipe heat exchanger is studied by a new model.
- Heat transfer and heat exchanger effectiveness are obtained for a porous media.
- The Darcy–Brinkman–Forchheimer and k–ε turbulent models are used.
- The sensitivity analysis is done using the Response Surface Methodology.
- The physical descriptions of results are illustrated by graphs and tables.

ARTICLE INFO

Article history:
Received 1 July 2016
Revised 16 August 2016
Accepted 20 August 2016
Available online 22 August 2016

Keywords:
Double pipe heat exchanger
Heat transfer
Porous medium
Sensitivity analysis
Turbulent flow

ABSTRACT

A 2-D numerical simulation and sensitivity analysis are carried out on turbulent heat transfer and heat exchanger effectiveness enhancement in a double pipe heat exchanger filled with porous media. The Darcy–Brinkman–Forchheimer and the k–ε turbulent models are employed to achieve heat transfer and heat exchanger effectiveness in the presented model. The sundry parameters Reynolds number ($3000 \leqslant Re \leqslant 5000$), Darcy number ($10^{-5} \leqslant Da \leqslant 10^{-3}$) and the porous substrate thickness ($1/3 \leqslant \delta \leqslant 1$) are studied. It is found that the mean Nusselt number increases by increasing the values of Reynolds number and dwindling of the Darcy number and porous substrate thickness. In addition, the heat exchanger effectiveness enhances with the Re and Da numbers and δ. The sensitivity analysis revealed that to maximize only the mean Nusselt number then it can be achieved for $Re = 5000$, $Da = 10^{-5}$ and $\delta = 1/3$. However, to maximize only the heat exchanger effectiveness then it attains at $Re = 5000$, $Da = 10^{-3}$ and $\delta = 1$. On the other hand, to maximize Nu and E simultaneously, then it can be obtained for $Re = 5000$, $Da = 10^{-5}$ and $\delta = 1$.

1. Introduction

Convective heat transfer in porous media plays an important role in numerous technological applications in various industrial applications such as food processing, geothermal heat extractions, solar collector technologies, spread of pollutants underground, storage of grains, heat removal from nuclear reactors, exothermic reactions in packs, bed reactors, electronic boxes and etc.; therefore, it has been considered by several researchers in different fundamental studies. Among these studies, porous media is considered by many to be one of the significant rudiments that will drive the next major industrial revolution of this century. In particular, here we can mention Lauriat and Ghafir [1] who have studied the enhancement of the heat and mass transfer in energy systems using porous medium. The values of Nusselt number are found to be 50% more than those of laminar flows in a channel without porous materials. A numerical investigation on constant wall heat flux boundary conditions in porous media has been done by Alazmi and Vafai [2] with considering local thermal non-equilibrium conditions. As it is clear, different boundary conditions may lead to different results. Vafai and Thiyagaraja [3] have investigated the interface between porous media and external fluid field, and also the porous media and a solid boundary. Vafai and Kim [4] have also

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http://dx.doi.org/10.1016/j.applthermaleng.2016.08.116
1359-4311/

Nomenclature

Cp	specific heat at constant pressure (J/kg K)
CF	inertia coefficient
D_h	hydraulic diameter, (m)
Da	Darcy number
E	heat exchanger effectiveness
h	convective heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
K	permeability of the porous layer (m^2)
k_e	effective conductivity of porous material
k	turbulent kinetic energy
L	length of the heat exchanger
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
p	pressure (Pa)
P	dimensionless pressure
Pr	Prandtl number
r	radial coordinate (m)
r_i	inner radius (m)
r_o	outer radius (m)
rp	porous radius (m)
R	dimensionless radial coordinate
Re	Reynolds number
R_k	thermal conductivity ratio, k_e/k_c
T	temperature (K)
u	axial velocity (m/s)
U	dimensionless axial velocity
v	radial velocity (m/s)
V	dimensionless radial velocity
x	axial coordinate (m)
X	dimensionless axial coordinate,

Greek symbols

ε	porosity
ρ	density (kg/m^3)
μ_l, μ_t, μ_e	laminar, turbulent and effective viscosity
σ_k, σ_ε, σ_t	k–ε turbulence model constant for k, ε and T
γ	binary parameter
θ	dimensionless temperature
μ	dynamic viscosity (kg/m s)

Subscripts

c	cold
e	effective
h	hot
i	inner
m	mean
o	outer
p	porous
w	wall

presented that the ratio of the effective thermal conductivity of the porous media to fluid thermal conductivity is the most effective parameter on the porous media thermal performance enhancement. Huang and Vafai [5] have studied the heat transfer of a flat plate which was mounted with porous block array. The results showed that the heat transfer rate on the flat plate decreases considerably due to the porous block array. Othman et al. [6] have performed an investigation on effect of magnetic field on the rotation of a thermoelastic medium with voids subjected to thermal loading due to laser pulse. This problem has been studied in the context of Green–Naghdi (GN) theory. A theoretical study on fluid mechanics of interface region between a porous medium and fluid layer has been presented by Vafai and Kim [7].

Additionally, the heat transfer performance in channels, tubes and heat exchangers filled with the porous materials has been a subject of interest in several researches such as: An experimental and numerical study on forced convection heat transfer in a rectangular channel filled with sintered bronze beads has been carried out by Tzeng [8]. The channel was composed of periodical spaced heat blocks, where the blocks were used to simulate heated electronic components, by sintered metallic porous media. They found that the cooling performance of heated blocks can be increased using the mentioned arrangement. A numerical analysis of flow and heat transfer characteristics in a double pipe heat exchanger with porous structures inserted in the annular gap has been done by Targui and Kahalerras [9]. Two different configurations have been considered in this study: first, on the inner cylinder; and second, on both the cylinders in a staggered fashion. The maximum heat transfer rates were observed when the porous structures are attached in second configuration at small spacing and high thicknesses. The forced convection heat transfer in an isothermal parallel-plate channel with porous block has been studied by Huang and Vafai [10]. The vorticity stream function formulation is utilized in this paper. The results showed that using of multiple emplaced porous blocks increases the heat transfer considerably. Alkam and Al-Nimr [11,12] have studied the transient developing forced convection flow in concentric tubes and circular channels, which were partially filled with porous materials. They found that the external heating penetration is more effective in the porous substrate than that of the clear fluid region. An experimental and numerical investigation on heat transfer enhancement for gas heat exchangers filled with porous media has been carried out by Pavel and Mohamad [13]. Their results revealed that using of porous inserts with a reasonable pressure drop penalty can leads to higher heat transfer rate. A numerical investigation on combined convection–radiation heat transfer rate and the pressure drop in a porous solar heat exchanger has been performed by Rashidi et al. [14]. They found that increasing the Darcy number reduces the pressure drop ratio in the vicinity of 58% and 23% for δ = 1/3 and 1, respectively and Da = 10^{-6} to 10^{-2}. Mohamad [15] has studied a numerical investigation on the heat transfer enhancement in heat exchangers filled with porous media. His results indicated that filling the channel partially with porous medium enhances the rate of heat transfer, and the pressure drop is less than that of a fully filled channel. Dehghan et al. [16] have done an investigation on combined heat transfer in heat exchangers filled with a fluid saturated cellular porous medium. They found that to simulate and predict of thermal performance of solar energy harvesting systems, the semi-analytical methods (like HPM, VIM, DTM, and HAM) can be used. Yucel and Guven [17] have performed a numerical study on convection cooling increase of heated elements in parallel-plate channels by porous inserts. They found that using of high-thermal-conductivity porous inserts increases heat transfer. Additionally, insertion of heated elements and porous matrix increases the Reynolds number and as a result, the pressure drop increases rapidly along the channel. Jung and Boo [18] have analyzed the radiation heat transfer in a high-temperature heat pipe heat exchanger. The results showed that the consideration of the radiant heat transfer enhances the heat transfer rate and makes the temperature distribution more uniform. The enhancement of heat transfer of a laminar flow in a circular duct has been carried out by Zhang et al. [19] numerically utilizing porous convection-to-radiation converter. The results illustrated that the porous core insertion in a circular duct increases both the convective heat transfer and