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Heat transfer and sensitivity analysis in a double pipe heat exchanger filled with porous medium

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In this paper, 2-D numerical investigation and sensitivity analysis are performed on heat transfer rate and heat exchanger effectiveness of a double pipe heat exchanger filled with porous medium. The Darcy–Brinkman–Forchheimer model is applied to model the flow field in the porous zone. The sensitivity analysis is performed utilizing the Response Surface Methodology. The studied parameters are: Reynolds number ($50 \leq Re \leq 250$), Darcy number ($10^{-5} \leq Da \leq 10^{-3}$), temperature difference between hot and cold fluids ($30 \leq \Delta T \leq 70$) and the porous substrate thickness ($1/3 \leq \delta \leq 1$). The obtained results showed that enhancement of the Nusselt number due to the increase in Reynolds and Darcy numbers is in the vicinity of the 77.84% for the case with $\delta = 2/3$ and $Da = 10^{-5}$ to 10^{-3}, and 203.25% for the case with $\delta = 1$ and $Re = 50$ to 250. Furthermore, increasing porous substrate thickness reduces the mean Nusselt number until $\delta = 2/3$ and then increases it. In addition, it is found that the heat exchanger effectiveness increases with the Re number and reduces with enhancement of the Da number. The sensitivity analysis showed that the sensitivity of the mean Nusselt number to the Re and Da numbers and the porous substrate thickness is positive, while the sensitivity of the heat exchanger effectiveness to the Re number is positive but to the Da number is negative.

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1. Introduction

Due to the important role of convective heat transfer in porous media and its several technological applications in related industries 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, etc., it has been a subject of interest in several fundamental researches in last decades. Among recent studies in this field, some researchers have studied heat transfer performance in heat exchanger without considering a porous medium [1–5]. For example, an experimental investigation on the effect of perforated discontinuous helical turbulators on heat transfer characteristics of double pipe water to air heat exchanger has been carried out by Sheikholeslami et al. [6]. The results showed that increasing the open area ratio and pitch ratio reduces the friction factor and Nusselt number. Also, the thermal performance increases with area ratio; but increasing the pitch ratio decreases the thermal performance. Chen and Dung [7] have performed a numerical investigation on heat transfer of parallel and counter flow double tube heat exchangers with alternating horizontal or vertical oval cross section pipes. They presented the temperature and pressure contours and velocity vectors at several selected cross sections. Also, axial averaged Nusselt number and overall heat transfer coefficient distributions and heat transfer enhancement factor based on three different parameters are obtained in this paper. Also, Bayer et al. [8] have performed a strategic optimization for a borehole heat exchanger. The results revealed that by supplying a given cooling and heating demand, the thermal impact on the long-term conditions in the ground can be minimized.

However, some researchers have studied heat transfer performance in channels, tubes and heat exchangers filled with the

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Nomenclature

ANOVA	Analysis of Variance
Cp	specific heat at constant pressure (J/kg K)
CCF	Face Centered Central Composite Design
CF	inertia coefficient
D_h	hydraulic diameter, (m)
Da	Darcy number
E	heat exchanger effectiveness
FVM	Finite Volume Method
h	convective heat transfer coefficient (W/m2 K)
k	thermal conductivity (W/m K)
K	permeability of the porous layer (m2)
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)
RMSE	Root Mean Square Error
R	dimensionless radial coordinate
Re	Reynolds number
R_k	thermal conductivity ratio, ke/kc
RSM	Response Surface Methodology
T	temperature (K)
u	axial velocity (m/s)
R	dimensionless radial coordinate
U	dimensionless axial velocity
ν	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)
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

porous materials. Targui and Kahalerras [9] have performed a numerical study to investigate the effect of porous baffles and flow pulsation on a double pipe heat exchanger performance. Their results revealed that the addition of an oscillating component to the mean flow increases the heat transfer. Additionally, the maximum performance of the heat exchanger is observed for the case in which only the flow of the hot fluid was pulsating. A numerical analysis of flow and heat transfer characteristics in a double pipe heat exchanger with porous structures inserted in the annular gap has also been done by Targui and Kahalerras [10]. Two different configurations have been considered in this study: on the inner cylinder; and on both the cylinders in a staggered fashion. The maximum heat transfer rates are observed when the porous structures are attached in second configuration at small spacing and high thicknesses. 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. 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. [13]. They found that increasing the Darcy number reduces the pressure drop ratio in the vicinity of 58% and 23% for $\delta = 1/3$ and 1, respectively and $Da = 10^{-6}$ to 10^{-2}. Dehghan et al. [14] 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. Pavel and Mohamad [15] have carried out an experimental and numerical study on the heat transfer enhancement for gas heat exchangers filled with metallic porous materials. The numerical code developed did not consider the radiative heat transfer. Jung and Boo [16] 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. Another investigation on combined heat transfer in heat exchangers filled with a fluid saturated cellular porous medium has been performed by Soltani et al. [17]. They analyzed exactly the effects of porous medium shape and radiation parameters on the thermal performance. Aguilar-Madera et al. [18] have investigated the convective heat transfer inside a channel, which was partially filled with a porous material. The results revealed that utilizing a channel fully filled with the porous material enhances the heat transfer rate. Moreover, in some studies, researchers have focused on Response Surface Methodology (RSM) to optimize the heat transfer rate, such as Mamourian et al. [19] and Milani-Shirvan et al. [20]. In these studies, the effective parameters on thermal performance in solar heat exchangers are investigated by Response Surface Methodology.

According to the literature review and to the best knowledge of the authors, despite the important applications of convective heat transfer in porous medium a numerical investigation and sensitivity analysis of effective parameters on heat transfer rate between two pipes of a double pipe heat exchanger filled with porous medium has not yet been considered. Furthermore, a sensitivity analysis is needed to evaluate the effects of Reynolds and Darcy numbers and porous substrate thicknesses on heat transfer rate and heat exchanger effectiveness inside a double pipe heat exchanger filled with porous medium. The sensitivity analysis of these parameters is done using the RSM method. Current investigation aims to obtain the optimal conditions to enhance the heat transfer rate and heat exchanger effectiveness in a double pipe heat exchanger in order to provide a useful guideline for researchers in the energy related fields. In general, the motivation in this article is based on the investigation of optimal conditions and sensitivity of the mean Nusselt number and heat exchanger effectiveness, of double pipe heat exchanger filled with porous media using the finite volume method (FVM) and RSM models.

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