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Heat transfer enhancement and pressure drop penalty in porous solar heat exchangers: A sensitivity analysis

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ABSTRACT

Porous materials have a positive effect upon the heat transfer enhancement and a negative impact on pressure drop. Combined convection–radiation heat transfer inside a porous solar heat exchanger with a sensitivity analysis is performed to calculate the effects of porous material on the heat transfer rate and the pressure drop. Reynolds and Darcy numbers and porous substrate thicknesses are selected as the influence parameters. The analysis is carried out by using Response Surface Methodology (RSM). Also, the input parameters for optimization process are obtained by numerical methods. The computational simulations are done for different Reynolds numbers ($1 \leqslant Re \leqslant 100$), Darcy number ($10^{-6} \leqslant Da \leqslant 10^{-2}$) and dimensionless porous substrate thickness ($1/3 \leqslant \delta \leqslant 1$). It is found that the reductions in pressure drop ratio with increasing Darcy number are in the vicinity of 58% and 23% for $\delta = 1/3$ and 1, respectively and $Da = 10^{-6}$–10^{-2}. Note that above values are obtained at $Re = 100$. However, the augmentation in Nusselt number with increasing the porous substrate thicknesses is in the vicinity of 96% for $\delta = 1/3$–1 and $Da = 10^{-2}$. Also, the maximum errors between the RSM and CFD results are in the vicinity of 3% and 1.37% for the Nusselt number and pressure drop ratio, respectively.

1. Introduction

Heat exchangers are equipment for transferring heat from one medium to another. The proper design, operation and maintenance of these devices can lead to improved energy efficiency and reduce energy losses. Some conditions such as fouling, corrosion and scaling have negative effects on the heat exchanger performance. These conditions not only have a negative impact on the heat transfer efficiency but also may restrict the output or production capacity of the facility.

Recently, some researchers have used porous materials for improving heat transfer in some equipment such as heat exchangers [1–6]. Porous materials are widely applied for the purification of gases and liquids, environmental protection, and human health protection. In the heat exchanger, these materials have many effects on the device efficiency and also can be used as purification of fluids inside these devices that leads to prevention or mitigation of corrosion and scaling. Note that the corrosion has the negative effects on the performance of heat exchangers.

First a comprehensive literature review on the researches in this field is necessary to classify the positive and negative impacts of these materials.

Some researchers studied the effects of porous inserts inside the heat exchanger channel. For example, Alkam and Al-Nimr [1,2] investigated the problem of transient developing forced convective flow in the concentric tubes and circular channels partially filled with porous materials. Their results revealed that the external heating has more effective penetration in the porous substrate than that in the clear fluid region. An experimental and numerical investigation on the heat transfer enhancement for gas heat exchangers filled with metallic porous materials have been done by Pavel and Mohamad [7]. In their study, the numerical code did not simulate radiative heat transfer. Convective heat transfer inside a channel partially filled with a porous material has been studied by Aguilar-Madera et al. [8]. They found that the heat transfer rate increases by using a channel fully filled with the porous insert. Radiation heat transfer analysis in the high-temperature heat pipe heat exchanger has been investigated by Jung and Boo [9]. It is found that the heat transfer rate increases and the temperature distribution becomes more uniform by considering radiant heat transfer. Dehghan et al. [10] studied analytically the forced convection in a circular tube filled with saturated porous medium by using local thermal non-equilibrium (LTNE) condition. They reported that increasing the conductivity ratio ($k = k_f/k_s$) and porosity of the medium leads to the decrease in ΔNE (dimensionless number representing the intensity of LTNE condition).

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Nomenclature

a	number of factors (–)
b	number of center points (–)
ANOVA	analysis of variance (–)
CCD	central composite design (–)
CCF	Central Composite Face centered (–)
CFD	computational fluid dynamics (–)
c_p	specific heat at constant pressure (J kg^{-1} K^{-1})
d	thickness of porous substrate (m)
D	half of the channel gap (m)
Da	Darcy number (–) (=KD^{-2})
DOE	design of experiments (–)
h	heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
K	permeability of the porous medium (m^2)
k_c	molecular thermal conductivity (W m^{-1} K^{-1})
k_r	radiative thermal conductivity (W m^{-1} K^{-1})
Nu	Nusselt number (–) (=hDK^{-1})
$\overline{Nu}$	surface-averaged Nusselt number (–)
$\langle\overline{Nu}\rangle$	time-averaged Nusselt number (–)
ΔP	pressure drop ratio (–)
P	pressure (Pa)
Pr	Prandtl number (–) (=$\nu\alpha^{-1}$)
Rc	thermal conductivity ratio (–) (=$k_{\text{eff}}k_f^{-1}$)
Re	Reynolds number (–) (=$\rho U\infty S\mu^{-1}$)
Res	response (–)
RSM	Response Surface Methodology (–)
t	time (s)
t_p	period of time integration (s)
T	temperature (K)
u, v	velocity component in x and y directions, respectively (m s^{-1})
x, y	rectangular coordinates components (m)

Greek symbols

α_0	average of the results of the replicated center point (–)
α_1, α_2, α_3	main half-effects of the coded variables A, B and C (–)
α_{11}, α_{22}, α_{33}	squared effects (–)
α_{12}, α_{13}, α_{23}	two factor interaction half-effects (–)
α	thermal diffusivity of fluid (m^2 s^{-1}) (=$k\rho^{-1}c_p^{-1}$)
β	stress jump parameter (–)
β_1	stress jump parameter related to inertia (–)
β_R	Rosseland mean extinction coefficient (m^{-1})
δ	dimensionless porous substrate thickness (–) (=dD^{-1})
ε	porosity (–)
μ	dynamic viscosity (kg m^{-1} s^{-1})
ν	kinematic viscosity (m^2 s^{-1})
σ	Stefan–Boltzmann coefficient (W m^{-2} K^{-4})
ρ	density of the fluid (kg m^{-3})
λ	radiation parameter (–)

Subscripts/superscripts

eff	effective
f	fluid
F	Forchheimer
m	mean
s	solid
w	wall
∞	free stream
$*$	dimensional variables
1	clear fluid domain
2	porous domain

Recently, convection–radiation heat transfer in solar heat exchangers filled with a porous medium has been studied by Dehghan et al. [11]. They used both homotopy perturbation and numerical analysis for simulating this problem. Also, they observed that the overall heat transfer increases by incorporating the radiation conductivity definition. Niu et al. [12] investigated the heat and mass transfer performance and cooling capacity prediction of earth to air heat exchanger.

Some researchers studied the heat transfer around a body that is placed inside a porous medium. For example, Rashidi et al. [13] investigated convective heat transfer from a cylinder embedded in porous medium. They recommend a porous medium with high permeability and thermal conductivity for heat exchanger applications. In another study, Magnetohydrodynamics flow and heat transfer around a solid cylinder wrapped with a porous ring have been investigated by Valipour et al. [14]. Their results indicate that the average Nusselt number does not change with the magnetic field for small Darcy numbers. The above discussions show that the heat transfer rate increases by using a highly conductive porous insert with high permeability.

Some researchers performed optimization analysis for regular heat exchanger (not porous heat exchanger). For example, Bellis and Catalano [15] performed a CFD optimization for an immersed particle heat exchanger. Strategic optimization for borehole heat exchanger has been done by Bayer et al. [16]. They observed that the thermal impact on the long-term conditions in the ground can be minimized while supplying a given cooling and heating demand. Also, some researchers focused on Response Surface Methodology for optimization [17,18]. For example, Bovand et al. [19] used Response Surface Methodology to optimize a standard Ranque–Hilsch vortex tube refrigerator. In another study, Sun and Zhang [20] evaluated the elliptical finned-tube heat exchanger performance using CFD and response surface methodology. They found that the increase of axis ratio is useful for the overall thermal–hydraulic performance at lower water volumetric flow rate. Recently, optimization of winglet-type vortex generator positions and angles in plate-fin compact heat exchanger has been done by Salviano et al. [21].

The literature review showed that the porous materials have a positive effect upon the heat transfer enhancement and a negative impact on pressure drop. Therefore, a sensitivity analysis is necessary to assess the validity of the above recommendations in practical applications and also to calculate the effects of Reynolds and Darcy numbers and porous substrate thicknesses on heat transfer rate and pressure drop inside a porous solar heat exchanger. The results from this research provide useful guidelines to the design of solar heat exchangers and can be used as initial data for selecting the different parameters for fabrication this device.

2. Mathematical formulation

2.1. Problem statement

The schematic of the computational domain is available in Fig. 1. As shown in this figure, the flow inside a heat exchanger with semi height of D is considered. Heat exchanger is partially or fully filled with porous material with thickness of d and heated from the exterior with a constant and uniform heat flux of q''. Also, the flow is assumed to be laminar, unsteady and incompressible with uniform velocity and temperature at the input of the heat