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Heat transfer enhancement and pressure drop penalty in porous solar heaters: Numerical simulations

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Abstract

A comprehensive numerical study is performed on the fluid flow and heat transfer within a porous solar heater. The effects of porous material on the heat transfer enhancement and pressure drop are presented in details. Also, the attention is focused on the effects of several parameters on the combined convection–radiation heat transfer and flow structures. Volume averaged equations are applied to simulate the transport phenomena within the porous substrate. Furthermore, the regular continuity, momentum, and energy equations are used in the clear fluid region. These equations are discretized using the control volume technique. It is found that the Nusselt number increases by inserting the porous substrate to the heater. These augmentations are up to 3, 4.4 and 5.9 times for $\delta = 1/3$, 2/3 and 1, respectively at $Da = 10^{-2}$. Also, the pressure drop increases with an increase in the porous layer thickness and decrease in the Darcy number.

Keywords: Solar heater; Convection–radiation; Finite volume method; Pressure drop; Darcy number

1. Introduction

Heaters are a part of everyday modern life with a wide range of industrial and engineering applications. Examples include the oil and gas industries, chemical processing, hydrocarbon processing, polymers, pharmaceuticals, and food and beverage (Bhutta et al., 2012). The efficiency of heaters is an important topic in these devices and provides a new way to design and analyze them. The ideal heater transfers the maximum amount of heat with lowest pressure drop. A new type of these devices is solar heater with many advantages such as endless amounts of energy, no CO_2 emissions during operation, cost savings and many other benefits. Recently, porous materials have been used in systems where the convection and radiation modes of heat transfer are both critical (Fuqiang et al., 2014; Lee et al., 2015; Hirasawa et al., 2013; Wang et al., 2013). These materials produce a pressure drop beside the heat transfer enhancement. A literature review on the related works to this topic is necessary in this stage.

Many studies have been conducted on the effects of porous material on the pressure drop or heat transfer (Xu et al., 2014; Chumpia and Hooman, 2015; Banerjee et al., 2015; Tsinoglou et al., 2004a,b; Martinopoulos et al., 2010; Missirlis et al., 2010; Missirlis et al., 2014). For example, forced convection in the developing region of a pipe partially filled with a porous layer has been investigated by Alkam and Al-Nimr (1998a). An external heating is used on the cylinder wall in their research. They found that the external heating has more effective penetration in the porous layer than that in the clear fluid region. In another

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Nomenclature

C_F	Forchheimer coefficient (–)
c_p	specific heat at constant pressure (J/kg K)
D	height of the channel $(m) D = 2R_2$
Da	Darcy number (–) $Da = K/D^2$
f	friction factor (–)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
K	permeability of the porous medium (m^2)
k_c	molecular thermal conductivity (W/m K)
k_r	radiative thermal conductivity (W/m K)
L	length of the heater (m)
Nu	Nusselt number (–) $Nu = \frac{q''(D)}{k_{eff}(T_w - T_m)}$
$\overline{Nu}$	surface-averaged Nusselt number (–)
$\langle \overline{Nu} \rangle$	time-averaged Nusselt number (–)
p	pressure (Pa)
Δp	pressure drop (Pa)
Pr	Prandtl number (–) $\mathrm{Pr} = \nu/\alpha$
Rc	thermal conductivity ratio (–) $Rc = k_{eff}/k_f$
Re	Reynolds number (–) $Re = \rho U_\infty D/\mu$
R_1	thickness of the porous substrate (m)
R_2	half of the channel gap (m)
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)
x, y	rectangular coordinates components (m)

Greek symbols

α	thermal diffusivity of the fluid (m^2/s) $\alpha = k/\rho c_p$
β	stress jump parameter (–)
β_1	stress jump parameter related to inertia (–)
β_R	Rosseland mean extinction coefficient (1/m)
δ	dimensionless porous substrate thickness (–) $\delta = R_1/R_2$
ε	porosity (–)
μ	dynamic viscosity (kg/m s)
ν	kinematic viscosity (m^2/s)
σ	Stefan-Boltzmann coefficient (W/m^2 K^4)
ρ	density of the fluid (kg/m^3)
λ	radiation parameter (–)
ζ	heat transfer enhancement (–)

Subscripts/superscripts

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

research, Al-Nimr and Alkam (1998b) investigated the fluid flow in the parallel-plate channels partially filled with the porous materials. They used Green's function method to obtain the analytical solution for modeling the fluid flow in the parallel-plate channels. Developing a 3-D computational model for the fluid flow and convective heat transfer in a channel partially filled with porous medium has been done by Jen and Yan (2005). It was found that there are two large vortices in the fluid region near the interface of the porous substrate with a pair of smaller vortices in porous substrate. This is due to the flow instability created by the blowing effect of the porous substrate. Convective heat transfer in a channel partially filled with a porous medium has been studied by Aguilar-Madera et al. (2011). They reported that the temperature profile is similar to the one found in a solid rod with the same dimensions as the channel for low values of the porosity. Aghajani Delavar and Mohammadvali (2013) simulated the convective heat transfer between two parallel plates with porous part using the Lattice Boltzmann Method. Their results showed that the temperature inside the porous block decreases with increase in Reynolds number. Recently, the local thermal non-equilibrium condition of porous media imbedded in the tube heaters has been studied by Dehghan et al. (2014). They found that the influence of Darcy number on the velocity field is more than its influence on the temperature field. Mahdavi et al. (2014) presented the entropy generation and convective heat transfer inside a pipe partially filled with a porous material. The porous layer was placed at the core of the pipe or it was attached to the inner wall. They found that the placement of porous medium at the tube wall leads to higher values of Nusselt number for high values of conductivity ratio and Darcy number. Torabi et al. (2015) performed the heat transfer and entropy generation analyses for a channel partially filled with porous media under the local thermal non-equilibrium conditions. They observed that the values of local and total entropy generation rates increase with decrease in Darcy number.

Throughout the past couple of years, some researchers have investigates the convection heat transfer from a body embedded in a porous medium. For example, the forced convection heat transfer from a single circular obstacle embedded in a porous region has been studied by Al-Sumaily et al. (2012). Their results indicated that the porous particles suppress significantly the unsteady hydrodynamic and thermal behaviors inside the channel. Rashidi et al. (2013) performed a study on the fluid flow and forced