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Numerical investigation and sensitivity analysis of effective parameters on combined heat transfer performance in a porous solar cavity receiver by response surface methodology

K. Milani Shirvan [a], M. Mamourian [a], S. Mirzakhanlari [b], R. Ellahi [c,d,*], K. Vafai [e]

[a] Department of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran
[b] Young Researchers and Elite Club, Qazvin Branch, Islamic Azad University, Qazvin, Iran
[c] Department of Mathematics & Statistics, FBAS, H-10 Sector IIUI, Islamabad, Pakistan
[d] Department of Mathematics, Taibah University, Madinah Munawwarah, Saudi Arabia
[e] Department of Mechanical Engineering, University of California Riverside, USA

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ABSTRACT

A numerical study on natural convection along with surface radiation heat transfer in an inclined porous solar cavity receiver by means of response surface methodology (RSM) is investigated. Discretization of the governing equations is first performed using a finite volume method and then solved with SIMPLE algorithm. Effects of physical parameters such as Rayleigh number ($10^4 \leqslant \mathrm{Ra} \leqslant 10^6$), Darcy number ($10^{-5} \leqslant \mathrm{Da} \leqslant 10^3$), inclination angles ($0° \leqslant \theta \leqslant 90°$), dimensionless porous substrate thickness ($1/3 \leqslant \delta \leqslant 1$), wall surface emissivity ($0 \leqslant \varepsilon \leqslant 1$) and surface radiation heat transfer rate are examined. The sensitivity analysis is also presented. It is found that the sensitivity of mean Nusselt number increases by increasing Rayleigh number, Darcy number and inclination angle θ whereas the sensitivity of mean Nusselt number of natural convection heat transfer to porous substrate thickness δ declines. Consequently increase in the thickness of porous substrate reduces mean Nusselt number of natural convection heat transfer. Also, the sensitivity of mean Nusselt number of natural convection heat transfer to Rayleigh number Ra, porous substrate thickness δ, Darcy number Da and the inclination angle θ is found to be higher than the mean Nusselt number of radiation heat transfer. However, the sensitivity of mean Nusselt number of radiation heat transfer to the surface emissivity ε is higher than the mean Nusselt number of natural convection.

1. Introduction

Underground heat pump system, solar engineering, material sciences, insulation materials, geophysical applications, air conditioning systems and grain storage are few important applications of natural convection and heat transfer. Due to massive applications, various numerical and experimental simulations have been done during the last few years to describe the natural convection and heat transfer with or without considering the thermal radiation in cavity. For instance, Desrayaud and Lauriat [1], Oztop et al. [2], Bahrehmand and Ameri [3], Basak et al. [4] and Ngo et al. [5] have studied a numerical modeling and optimization on natural convection heat loss suppression in a solar cavity receiver with plate fins. They have found a considerable reduction in the natural convection heat loss from the cavity receivers may be obtained utilizing the plate fins.

Moreover, surface radiation has also gained considerable attention of many researchers due to its vast range of application. For example, Polat and Bilgen [6] have done a numerical investigation on combined effects of natural convection and surface radiation heat transfer in an inclined open shallow cavity. They have detected that for a given aspect ratio and Rayleigh number, the Nusselt number is maximized at an optimum aspect ratio. Another study on combined natural convection and surface radiation in an open cavity has been reported by Balaji and Venkateshan [7]. They have considered the interaction between natural convection and surface radiation heat transfer and found that the total heat transfer increases with radiation, depending on the radiative parameters. A study on the natural convection and surface thermal radiation heat transfer in a square tilted open cavity has been done numerically by Hinojosa et al. [8]. The presented results reveal that the Nusselt number of natural convection vicissitudes considerably

* Corresponding author at: Department of Mathematics, Taibah University, Madinah Munawwarah, Saudi Arabia.
E-mail addresses: rellahi@engr.ucr.edu, rahmatellahi@yahoo.com (R. Ellahi).

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Nomenclature

Cp	specific heat($\mathrm{J\,kg^{-1}\,K^{-1}}$)
Da	Darcy number
F_{ij}	view factor between surfaces i and j
g	gravitational acceleration ($\mathrm{m\,s^{-2}}$)
H	height and width of the cavity (m)
k	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
Nu	local Nusselt number
p	pressure ($\mathrm{N\,m^{-2}}$)
P	dimensionless pressure
Pr	Prandtl number
q''_0	heat flux ($\mathrm{W\,m^{-2}}$)
Re	Rayleigh number
T	temperature (K)
u, v	velocity components along x-axis and y-axis, respectively ($\mathrm{m\,s^{-1}}$)
U, V	dimensionless of velocity component
x, y	x and y axis coordinates, respectively
X, Y	dimensionless Cartesian coordinates

Greek symbols

α	thermal diffusivity, $k/(\rho cp)$ ($\mathrm{m^2\,s^{-1}}$)
β	thermal expansion coefficient, ($\mathrm{K^{-1}}$)
δ	dimensionless porous substrate thickness ($\delta = \mathrm{DH^{-1}}$)
ε	surface emissivity
γ	dimensionless temperature
μ	dynamic viscosity ($\mathrm{kg\,m^{-1}\,s^{-1}}$)
υ	kinematics viscosity ($\mathrm{m^2\,s^{-1}}$)
ρ	density ($\mathrm{kg\,m^{-3}}$)

Subscripts

c	convective
i,j	ith and jth subdivisions
r	radiation
s	surface

with an inclination angle of the cavity while the variation of the radiation Nusselt number is almost negligible. Gonzalez et al. [9] have investigated a numerical study on natural convection and surface thermal radiation heat transfer in an open cavity receiver by considering high temperature differences along with variable fluid properties. They have shown that the radiation heat transfer is more important than the convection heat transfer. A 2-D numerical study on the natural convection and surface radiation heat transfer in an open cavity has been probed by Singh et al. [10]. In this study, the effect of the various positions of the uniform volumetric heat generating source on the left side wall of the cavity has been considered and effective cooling is achieved due to locating the heat source at the top of the left wall. Ngo et al. [11] have studied a numerical and optimization analysis on combined natural convection and surface radiation heat transfer in a solar cavity receiver with plate fins. The attained results indicate that the number of fins in the receiver is largely effective on convection heat loss and the properties of the cavity receiver surface are also affected due to inclination angle of the receiver. On the other hand, the radiation heat loss has been found constant for the rest of all angles of receiver. Some relevant studies on heat transfer can be found in [12–18] and several references therein.

Furthermore, several studies have also been done on natural convection in cavities that are fully or partially filled with porous medium, such as Anandalakshmi et al. [19] have performed a numerical study to analyze the natural convection in a right-angled triangular cavity filled with porous media. They found that the maximum heat flux at the top vertex decreases by increasing the inclination angle to 45°. Hadidi et al. [20] have done a numerical study on the double diffusive convection generated in a horizontal bi-layered porous cavity. An analysis on entropy generation for uniform and distributed heating systems has been performed by Kaluri and Basak [21]. Natural convection for fluids in square cavities filled with porous medium is considered in this study. They found that larger thermal mixing at high Darcy numbers may not be suggested always, since the total entropy production is quite large at high Darcy numbers. Sheremet et al. [22] have investigated a numerical study on natural convection in a porous cavity with a nanofluid using LTNE model. They have found that the addition of nanoparticles to the base fluid overcomes the convective flow. In addition, solar cavity receiver and double pane window buildings are also hot topics of combined natural convection and radiation heat transfer between surfaces [23]. Thus, investigating the interaction of surface thermal radiation and natural convection in an open cavity is need of the day.

A very careful literature review bears witness that an investigation on sensitivity analysis of the effective parameters in a cavity receiver heat transfer rate has not yet been available in the existing literature. Therefore, keeping in view the importance and various applications of the solar receivers and the effect of the porous medium on enhancement of the heat transfer rate, a sensitivity analysis of effective parameters on combined natural convection and surface radiation heat transfer rate in a solar cavity receiver is presented in order to fill this gap. The Rayleigh number, Darcy number, inclination angle, porous substrate thickness and the wall surface emissivity are examined as the effective parameters using the RSM models. Additional objective of this innovative investigation is to achieve the optimal conditions to increase the heat transfer rate in porous solar cavity receivers which is fully or partially filled with porous material and may provide a useful guideline for researchers of solar energy related fields.

2. Problem statement

The schematic geometry of the porous solar cavity receiver, which is fully or partially filled with porous material with δ thickness ($=\frac{D}{H}$), is depicted in Fig. 1. The geometry is consisted of two-dimensional open square cavity with left side hot wall under constant heat flux and insulated top and bottom horizontal walls.

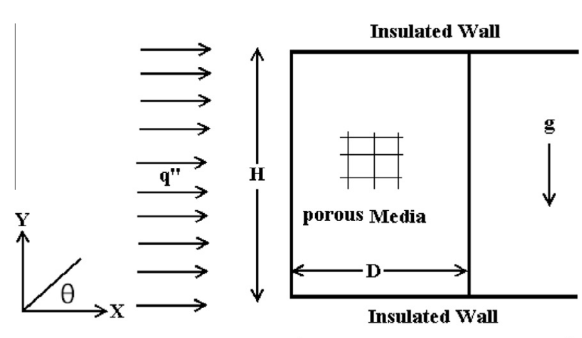

Fig. 1. The schematic of the porous solar cavity receiver.