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Heat flow visualization during mixed convection within entrapped porous triangular cavities with moving horizontal walls via heatline analysis

Monisha Roy [a], Pratibha Biswal [b], S. Roy [a], Tanmay Basak [b,*]

[a] Department of Mathematics, Indian Institute of Technology Madras, Chennai 600036, India
[b] Department of Chemical Engineering, Indian Institute of Technology Madras, Chennai 600036, India

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A B S T R A C T

This paper analyzes the fluid and heat flow within entrapped porous triangular cavities involving various thermal boundary conditions (case 1: hot horizontal walls and cold inclined walls; case 2: cold horizontal walls and hot inclined walls). Finite element based numerical study has been performed for various values of Prandtl number ($Pr_m = 0.026$ and 7.2), Darcy number ($Da_m = 10^{-4} - 10^{-2}$), Reynolds number ($Re = 1 - 1000$) at a high value of Grashof number ($Gr = 10^5$). The upper cavity for the case 1 and the lower cavity for the case 2 show almost similar trends and vice versa based on the exact opposite thermal boundary conditions. Heat transfer is conduction dominant at $Da_m = 10^{-4}$ involving both Pr_m whereas, convection heat transfer dominates at $Da_m = 10^{-2}$ especially for $Pr_m = 7.2$. Although the motion of the horizontal walls significantly influences the fluid flow field within the cavities, due to the decoupling between the fluid and thermal fields at the low Pe_m ($Pe_m = 0.026$, 0.26 and 2.6), conduction dominant heat transfer occurs. At the high Da_m and $Pr_m = 7.2$, a pair of symmetric streamline or heatline cells are seen for $Re \leq 1$ whereas, a bigger primary streamline or heatline cell is accompanied by a secondary streamline or heatline cell for $1 \leqslant Re \leq 100$. At $500 \leqslant Re \leqslant 1000$, the single larger streamlines or heatline cells are seen especially for $Pr_m = 7.2$ involving $Da_m = 10^{-2}$. At $Pr_m = 0.026$, the average heat transfer rates ($\overline{Nu_t}$, $\overline{Nu_b}$, $\overline{Nu_l}$ and $\overline{Nu_r}$) are almost constant with Re and Da_m. At $Pr_m = 7.2$, the larger magnitudes of$\overline{Nu_t}$ and $\overline{Nu_l}$ are observed for $Re \leq 10$ compared to those for $Re = 100$ involving $Da_m \geqslant 10^{-3}$ whereas, the magnitudes of $\overline{Nu_r}$ are almost similar for all Re involving all Da_m in the upper cavity (case 1) within $Re \leqslant 100$. In the lower cavity (case 1), the magnitudes of $\overline{Nu_b}$ and $\overline{Nu_r}$ are larger for $Re = 100$ whereas, the magnitudes of $\overline{Nu_l}$ are larger for $Re \leq 1$ for almost entire range of Da_m within $Re \leq 100$ involving $Pr_m = 7.2$. The average Nusselt numbers are significantly larger at the high Re ($Re = 500$ and 1000) involving all Da_m (except for the horizontal walls involving $Da_m \leqslant 8 \times 10^{-4}$) in the cases 1 and 2 at $Pr_m = 7.2$.

1. Introduction

Mixed convection heat transfer influences the performance of the thermal systems involving various physical applications such as ventilation in rooms [1], galvanization [2], nuclear reactors [3], food processing [4], glass production [5], solar power collectors [6], drying technologies [7], heat exchangers [8,9], bearing and lubrication systems [10] to name just a few of them. In addition to the fluid media, porous media involving mixed convection have received attention due to its applications in cooling of electronic devices [11], solar chimney and solar wall [12], heat exchanger [13] etc.

Over the years, enclosures with various shapes filled with the porous medium involving various velocity and thermal boundary conditions during mixed convection have been studied. Khanafer and Chamkha [14] studied mixed convection heat transfer within the square cavity filled with the porous medium for adiabatic side walls and isothermal horizontal walls using Darcy-Brinkman model. Oztop [15] analyzed the mixed convection heat transfer in a porous square cavity subject to partially heated left wall, moving cold top wall and adiabatic bottom and side walls using Darcy-Brinkman-Forchheimer model. Kandaswamy et al. [16] considered porous media filled lid driven square cavity involving the hot bottom wall, cold top wall and adiabatic side walls.

* Corresponding author.
E-mail addresses: monisha.roy97@gmail.com (M. Roy), biswal.pratibha9@gmail.com (P. Biswal), sjroy@iitm.ac.in (S. Roy), tanmay@iitm.ac.in (T. Basak).

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Nomenclature

Da	Darcy number
Da_m	modified Darcy number
g	acceleration due to gravity, m s^{-2}
Gr	Grashof number
k	thermal conductivity, W m^{-1} K^{-1}
K	medium permeability
L	base of the triangular cavity, m
n	normal vector to the plane
Nu	Nusselt number
$\overline{Nu}$	average Nusselt number
p	pressure, Pa
P	dimensionless pressure
Pe	Peclet number
Pe_m	modified Peclet number
Pr_f	Prandtl number
Pr_m	modified Prandtl number
Re	Reynolds number
Ri	Richardson number
T	temperature of the fluid, K
T_h	temperature of hot wall, K
T_c	temperature of cold wall, K
u	x component of velocity, m s^{-1}
U	x component of dimensionless velocity
U_0	dimensionless characteristic velocity
v	y component of velocity, m s^{-1}
V	y component of dimensionless velocity
x	distance along x coordinate, m
X	dimensionless distance along x coordinate
y	distance along y coordinate, m
Y	dimensionless distance along y coordinate

Greek symbols

α	thermal diffusivity, m^2 s^{-1}
β	volume expansion coefficient, K^{-1}
ϵ	porosity
γ	penalty parameter
θ	dimensionless temperature
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
ψ	dimensionless streamfunction
Π	dimensionless heatfunction
μ	dynamic viscosity, kg m^{-1} s^{-1}

Subscripts

av	spatial average
eff	effective
f	fluid

Superscripts

e	element

Vishnuvardhanarao and Das [17,18] and Kumar et al. [19] investigated mixed convection heat transfer for differentially heated square cavity involving moving side walls using Darcy-Brinkman and Darcy-Brinkman-Forchheimer models, respectively. Oztop and Varol [20] investigated mixed convection fluid flow and heat transfer within inclined porous square cavity heated from one wall with a non-uniformly heater, using Darcy-Brinkman-Forchheimer model. Muthtamilselvan et al. [21] studied the mixed convection flow in a porous square cavity for moving isothermally hot bottom and cold top walls in the presence of adiabatic vertical walls using Darcy-Brinkman-Forchheimer model. The numerical investigation on heat transfer during mixed convection in a square cavity for the flexible hot bottom wall, cold moving top wall and adiabatic side walls was investigated by Al-Amiri and Khanafer [22]. A comprehensive analysis on the fluid flow and heat transfer involving mixed convection within the square cavity filled with saturated porous medium for the isothermally or non isothermally heated bottom wall was done by Basak et al. [23] using Darcy-Brinkman model. Ramakrishna et al. [24] utilized the heatline concept to analyze the convection phenomena for various thermal aspect ratio applied at the bottom and side walls in the presence of the adiabatic moving top wall. Darcy-Brinkman-Forchheimer model based mixed convection process in square enclosures filled with the saturated porous medium for moving horizontal walls was performed by Oztop et al. [25]. Alshriaan [26] examined the convection heat transfer in a vented square cavity filled partially with a porous medium using Darcy-Brinkman-Forchheimer model. Al-Amiri [27] studied the effect of the presence of a porous block on the heat transfer during mixed convection in a square cavity involving the hot bottom wall, cold moving top wall and adiabatic vertical walls.

A few studies have been done on the mixed convection process within triangular cavities filled with various fluids. Chen and Cheng [28] examined the fluid flow and heat transfer in a triangular enclosure involving hot side walls and cold oscillating horizontal wall. Chen and Chung [29] investigated mixed convection heat transfer for various inclination angles of a triangular cavity with the identical thermal boundary conditions as mentioned in the earlier work [28]. The parametric studies on the mixed convection heat and mass transfer in right angled triangular cavities involving the hot bottom wall, cold hypotenuse and adiabatic moving vertical wall were carried out by Ching et al. [30] and Hasanuzzaman et al. [31].

The influence of the lid's motion on the fluid and heat flow patterns during the convection process within the triangular cavity filled with porous media for various industrial applications has not been explored yet. Thus, the aim of the current study is to get an insight on the heat transport mechanisms within an entrapped triangular enclosure involving moving horizontal walls. The investigation of heat transfer phenomena within the entrapped triangular cavity has important applications for the indirect contact heat exchanger in the process industry. In the current study, a series of entrapped triangular cavities (aspect ratio = 1:2) are formed due to the group of horizontally placed diamond shaped tubes associated with a pair of horizontal movable plates [see Fig. 1(a)]. The fluid with a constant temperature passes through the stack of the diamond shaped tubes whereas the entrapped triangular cavities are filled with fluid saturated porous media at different temperatures so that (i) the entrapped fluid is steadily heated in the triangular porous media (case 1: hot fluid disposal within the tubes) or (ii) the entrapped fluid is cooled in the triangular porous media (case 2: cold fluid disposal within the tubes). The effect of the lid velocity on heat flow fields is explored utilizing the heatline concept. The key parameters for this analysis are considered as Darcy number (Da_m), Prandtl number (Pr_m), Grashof number (Gr) and Reynolds number (Re). Finally, the heat recovery for various fluid saturated porous media has been evaluated via average Nusselt numbers.