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Analysis of heatline based visualization for thermal management during mixed convection of hot/cold fluids within entrapped triangular cavities

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ABSTRACT

A comprehensive investigation has been carried out to analyze the fluid and heat flow during mixed convection in entrapped triangular cavities for heat disposal (case 1: hot inclined and cold horizontal wall) and heat recovery (case 2: cold inclined and hot horizontal walls) to/from the industrial fluids via heatline approach. Galerkin finite element method is employed to solve the governing equations and the results are illustrated for various Grashof numbers ($10^3 \leq Gr \leq 10^5$), Prandtl numbers ($Pr = 0.026$ and 7.2) and Reynolds numbers ($1 \leq Re \leq 100$). At $Re = 1$, the symmetric fluid circulation cells occur whereas, the asymmetric fluid circulation cells occur at $Re \geq 10$ and $Gr = 10^5$ in both the cases and both Pr. The conduction dominant heat transfer is observed at $Pr = 0.026$ and $Gr = 10^5$ involving all Re. In contrast to $Pr = 0.026$, the heat flow field is highly influenced by the fluid flow field at $Pr = 7.2$ for all Re and $Gr = 10^5$. In the upper cavity, the average Nusselt number of the top wall ($\overline{Nu_t}$) is higher at $Re \to 0$, $Gr = 10^5$ for the case 1, and at $Re = 100$, $Gr = 10^3$ for the case 2 involving $Pr = 7.2$. In the lower cavity, the average Nusselt number of the bottom wall ($\overline{Nu_b}$) is higher at $Re = 100$, $Gr = 10^3$ for the case 1, and at $Re \to 0$, $Gr = 10^5$ for the case 2 involving $Pr = 7.2$.

1. Introduction

Convective transport has been investigated significantly due to various applications which include the heat exchanger [1,2], drying [3], electronic equipments cooling [4], chemical reactors [5,6] *etc.* Based on the practical applications, various works on mixed convection heat transfer heat transfer are found in the literature for systems involving magnetohydrodynamic mixed convection and nanofluids [7–14], double diffusive mixed convection [15,16], mixed convection involving radiative flow [17] *etc.* It was found from the literature that, the problem of mixed convection within enclosed cavity in the presence of moving wall (s) is one of the challenging issues and many research works have been reported in the literature to address mixed convection flows within enclosures with different geometrical structures.

Several studies have been reported on mixed convection in square and rectangular cavities since last decades. Ghasemi and Aminossadati [18] investigated the unsteady mixed convection heat transfer within a square cavity involving partially hot left wall, isothermally cold moving right wall involving adiabatic horizontal walls. Further, Waheed [19] analyzed mixed convection heat transfer in a rectangular enclosure involving adiabatic right vertical wall, cold left, bottom and top walls with a moving hot horizontal wall which divided the rectangular domain into two halves. The study of mixed convection fluid flow and heat transfer within the square cavity involving the isothermally or non-isothermally heated bottom wall, cold side walls and well insulated moving top wall was carried out by Basak et al. [20]. Further, Basak et al. [21] studied flow and thermal characteristics within the square cavity for isothermally hot bottom wall, linearly heated side wall and adiabatic moving top wall. Cheng and Liu [22] investigated heat transfer in an inclined square cavity with isothermally hot bottom wall, cold top wall and adiabatic side walls involving the moving lid. Khanafer [23] examined mixed convection heat transfer within square cavity for isothermally hot top wall, cold, flexible bottom wall involving various wavy shapes and adiabatic side walls. Ismael et al. [24] studied mixed convection heat flow in a square cavity involving partial slip imposed on the moving horizontal walls.

In addition to the enclosures with regular geometries, mixed convection studies within enclosures with irregular geometries

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Nomenclature

g	acceleration due to gravity, m s^{-2}
Gr	Grashof number
k	thermal conductivity, W $m^{-1}K^{-1}$
L	Base of the triangular cavity, m
n	normal vector to the plane
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
p	pressure, Pa
P	dimensionless pressure
Pe	Peclet number
Pr	Prandtl number
Re	Reynolds number
Ri	Richardson number
S	length of the side walls
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
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^2s^{-1}
β	volume expansion coefficient, K^{-1}
γ	penalty parameter
θ	dimensionless temperature
ν	kinematic viscosity, m^2s^{-1}
ρ	density, kg m^{-3}
ψ	dimensionless streamfunction
Π	dimensionless heatfunction
μ	dynamic viscosity, kg $m^{-1}s^{-1}$

subjected to different boundary conditions are also carried out. Chang and Cheng [25] analyzed mixed convection in an arc shaped cavity with isothermally hot moving horizontal wall and isothermally cold curved wall. Further, Chen and Cheng [26] studied the convective heat transfer within arc shaped enclosure with isothermally cold moving horizontal wall in the presence of isothermally hot curved wall. Also, Chen and Cheng [27] and Chen and Chung [28] also analyzed mixed convection heat in inclined arc shaped enclosures involving a moving lid. In addition, Chen et al. [29] carried out experiment to validate the earlier numerical work [26] and showed that the numerical results are in well agreement with the experimental results. Ilham et al. [30] examined mixed convection heat transfer in a trapezoidal cavity with hot bottom wall, cold top wall and adiabatic side walls involving various positions of inlet and outlet. Bhattacharya et al. [31] analyzed and discussed about the occurrence of the steady state multiple solutions during mixed convection within a trapezoidal cavity for isothermally cold moving top wall, hot bottom wall and adiabatic side walls. Numerical investigation of mixed convection within trapezoidal cavities involving adiabatic horizontal walls, cold left wall and hot moving right wall was carried out by Ismael and Chamkha [32].

A few studies have been performed on mixed convection process within triangular shaped cavities. Chen and Cheng [33] studied heat transfer analysis in a triangular enclosure with hot side walls and cold oscillating horizontal wall. Their study concludes that, the average Nusselt number is increased with the frequency of the lid velocity. Further, Chen and Chung [34] extended their study to investigate mixed convection heat transfer in inclined, differentially heated triangular cavity involving moving lid for various inclination angles. Ching et al. [35] and Hasanuzzaman et al. [36] examined mixed convection heat and mass transfer in a right angle triangular cavity involving hot bottom wall, cold hypotenuse and adiabatic moving vertical wall. Their result indicates that heat and mass flow rates are highly influenced by the directions of the moving lid.

Based on the foregoing review, it is found that the influence of the lid velocity on the triangular cavity flows is not addressed in detail. Thus, the aim of current work is to analyze the details of flow and thermal characteristics during mixed convection in an entrapped triangular cavity. The heat transfer application involving entrapped triangular cavity can be found in indirect contact heat exchanger in the process industry. To the authors' knowledge, the detailed study of heat flow visualization during the hot or cold fluid disposal in a system involving series of entrapped triangular cavities is not carried out so far. In the present work, a series of entrapped triangular cavities involving aspect ratio = 1: 2 are considered. Note that, the series of entrapped triangular cavities is originated from a series of horizontally placed diamond shaped tubes (see Fig. 1(a)). The system of diamond shaped tubes and entrapped triangular cavities consist of top and bottom moving walls (see Fig. 1(a)). The fluid with some constant temperature passes through the stack of the diamond shaped tubes and entrapped triangular cavities are filled with fluid at different temperature so that heat is removed to the fluid entrapped in the triangular cavity (case 1) or released to the fluid entrapped in the triangular cavity (case 2). The effect of the lid velocity on the heat transfer characteristics via heatline analysis within entrapped triangular cavities is the key issue of the present study. This numerical study may be useful in various indirect heat transfer applications.

2. Mathematical modeling, numerical simulation and post-processing

2.1. Governing equations, boundary conditions and numerical simulations for velocity and temperature fields

The physical and computational domains of entrapped triangular cavities are shown in Fig. 1(a) and (b). Based on thermal boundary conditions along the cavity walls, two cases are considered for the current study. The case 1 corresponds to the enclosures with hot inclined walls and cold horizontal walls whereas, the case 2 corresponds to the enclosures with cold inclined walls and hot horizontal walls. The horizontal walls move in their own plane (in positive X direction) with the uniform velocity, U_0 for both the cases. The flow field is steady, laminar and two-dimensional. The fluid is assumed to be incompressible. The variations of the thermophysical properties are ignored except for the density as the density variation induces natural convection flow. The density variation with temperature in the body force term in the Y momentum balance equation is governed by the Boussinesq approximation. The governing equations in terms of the non-dimensional variables and parameters can be derived based on the above assumptions and those are written as follows:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0\,, \tag{1}$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{1}{Re}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right), \tag{2}$$

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \frac{1}{Re}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + \frac{Gr}{Re^2}\,\theta\,, \tag{3}$$

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