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A computational study on mixed convection in a porous media filled and partially heated lid-driven cavity with an open side

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Abstract Applications of mixed convection due to lid-driven cavities can be found in different engineering technologies. A computational study was conducted to explore the effects of different parameters on mixed convection in a porous media filled lid-driven cavity with one side opening in the presence of heat generation. The cavity has a flush mounted heater on its bottom wall. The governing equations were solved by developing a computer code by using finite volume technique for different parameters as length of heater (1/5, 2/5, 4/5), Richardson number (0.1, 1, 10) and Darcy number (0.1, 0.01, 0.001). It is found that heat transfer and flow field inside the cavity is so complex due to moving lid, open side wall and heater. Heat transfer increases with increasing of Grashof numbers, heater length and decreased with Darcy numbers.

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1. Introduction

Mixed convection due to lid-driven cavities can be find applications in different engineering technologies such as moving belts near objects, cooling of electronical equipments, ocean engineering and automotive engines. The media can be pure air, water, nanofluid or porous media. Convection associated with porous media has been investigated extensively in the past few decades due to its numerous engineering applications [1–3].

Most of the studied systems in engineering have finite length heater such as house heating systems, electronic equipments or local heating systems. In this perspective, a reviewal work was made by Oztop et al. [4] to show the applications of partial heating for different systems. Ahmed et al. [5] analysed the natural convection including radiation heat transfer in a partially heated cavity. Oztop et al. [6] investigated the natural convection in a partially opened porous cavity. They found that increasing the porosity of the cavity's interior increases the heat transfer rate. They also deduced that there are an optimum opening location for each value of porosity. Chung and Vafai [7] researched the effect of vibration on the heat convection in an open-ended porous enclosure. The opening in their study is at the top. They found that increasing the vibration of the left wall resulted in enhanced heat transfer.

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Nomenclature

c	Center of heater
C_F	Forchheimer constant
Da	Darcy number
g	gravitational acceleration
Gr	Grashof number
h	length of the heated wall
H	length of the square cavity
K	permeability of the porous medium
n	normal to the wall
Nu_x	local Nusselt number
Nu_m	mean Nusselt number
p	dimensional pressure
P	dimensionless pressure
Pr	Prandtl number
Re	Reynolds number
Ri	Richardson number
T	fluid temperature
u', v'	dimensional velocity components along x- and y-axes
U, V	dimensionless velocity components along X- and Y-axes
x', y'	dimensional Cartesian coordinates
X, Y	dimensionless coordinates
w	length of heater

Greek letters

α	thermal diffusivity
β	thermal expansion coefficient
ε	porosity
H	dimensionless temperature
μ	kinematic viscosity
ϕ	any dependenet parameter
Θ	dimensionless temperature

Subscripts

c	cold
h	hot
int	interior

They also found that reducing the prosity, increases the effectiveness of the vibration in enhancing the heat transfer. Biswas and Manna [8] in their study concluded that the aspiration can impressively increase heat transfer without any extra pumping power expenditures for it. Oztop [9] performed a work on combined convection heat transfer associated with porous media filled a lid-driven cavity that is partially-heated from the bottom wall. He observed that parameters for heater are the most important on fluid flow and heat. Singh and Singh [10] provided a numerical solution of 2D natural convection and developed correlations for highest heat source non-dimensional temperature for three various positions on the wall. The open cavity presents the challenge of boundary conditions at the opening and they effectively affect the flow and heat transfer inside the enclosure (Khanafer and Vafai [11] and Khanafer et al. [12]). Carefull implemenation is necessary to avoid artificial effects at the open boundary. Alternatively, extending the computation domain to reach the far field allows the approximation of zero gradients for velocity and temperature to be accurate enough for engineering purposes. Rutt and Grosan [13] studied the lid-driven porous media cavity problem both numerically and analytically. Sheikholeslami and Shamlooei [14] solved the nanofluid filled lid-driven cavity problem by using CVFEM method in the existence of magnetic field. They observed a decrease in the convective heat transfer as Hartmann number improves but it enhances with enhancing of Reynolds and Darcy numbers. Effects of Peclet number on fluid flow and mixed convection heat transfer in a lid-driven trapezoidal shaped porous cavity was studied by Chattopadhyaya and Pandit [15]. They indicated that the intensity of the flow was reduced for higher Prandtl number, namely $Pr = 10$, due to the less intensity of buoyancy that is resulted from large isothermal cold fluid inside the cavity. Similarly, Al-Amiri [16] worked on the transfer of energy and momentum in a porous media filled enclosure. They used control volume approach to solve governing equations. A study was conducted by Basak et al. [17] on mixed convection in a lid-driven closed space willed with a porous medium. Oztop [18] studied on porous media filled rectangular enclosures with partial cooler length by using finite volume method and found that the cooler length is the most important parameter on heat and fluid flow in the system.

Lattice Boltzmann technique was used by Chen et al. [19] in their natural convection study on partially-filled with porous media in a square cavity that is open-ended. They found that a large change of heat and mass transfer was resulted as a response to small offset. Biswas et al. [20] in their heat transfer and pumping power study for a porous cavity that is heated from bottom wall. Despite the changes in parameters, they found a fixed flow pattern persists. The heat transfer improvement attributable to nanoparticles is evaluated. Shi and Vafai [21] performed a mixed convection study of a cavity that is obstructed by heated horizontal walls and found an increase in the thickness of the thermal boundary layer as the aspect ratio increases. Khanafer and Vafai [22] conducted a numerical study on a non-Darcian fluid-saturated porous medium filling a lid-driven square enclosure. Their focus was the effect of this case on mixed-convection heat and mass transport. They observed that the Lewis number, Darcy number, buoyancy ratio, and Richardson number have great influences on the double-diffusive phenomenon. Sheikholeslami [23] used the LBM to investigate the a nanofluid's free convection in an open porous cavity and how it is affected by the magnetic field. Ahmed [24] solved a mixed convection problem for double sided lid-driven cavity filled with thermally anisotropic non-Darcy porous medium. He used heatlines technique to simulate heat transport way. Rajarathinam et al. [25] solved a three different cases mixed convection problem for an inclined Cu-nanofluid-saturated porous cavity. They showed that a significant role exists for the flow and heat transfer with the moving wall's direction. Penalty finite element analysis was used by Basak et al. [26] to study mixed convection of a porous

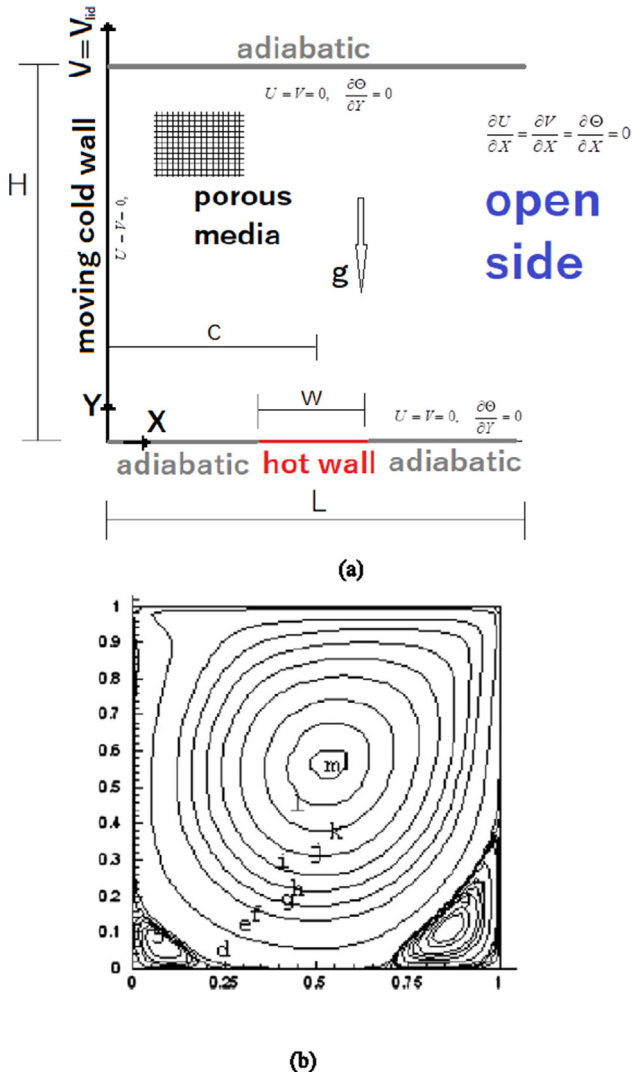

Fig. 1 (a) Physical Model, (b) Streamlines for $Re = 1000$ for validation.

Table 3 Mean Nusselt number comparison between literature and this study for $Da = 0.1$.

Ri	$\overline{Nu}(present)$	Nu [29]	% deviation
0.1	4.196	3.92	6.5
1	2.312	2.31	0
5	1.746	1.83	4.5

Table 4 Comparison of mean Nusselt numbers with literature studies from ref. Oztop [30].

Study	Results
Baytas [31]	3.160
Saeid and Pop [32]	3.002
Present	2.980

Table 5 Verification of the streamfunction values with literature [37,38].

Present study		Refs. [37,38]	
d	$-0.92\text{x}10^{-4}$	d	$-1.0\text{x}10^{-4}$
e	−0.0061	e	−0.01
f	−0.025	f	−0.03
g	−0.039	g	−0.05
h	−0.053	h	−0.07
İ	−0.08	İ	−0.09
J	−0.094	J	−0.1
k	−0.103	k	−0.11
l	−0.108	l	−0.115
m	−0.11	m	−0.1175

Table 1 Source term as given in Eq. (1) (Oztop [9]).

Equation	S
Continuity	0
x-momentum	$-\varepsilon^{+2}\frac{\partial P}{\partial X}+\frac{\partial}{\partial X}\Gamma\frac{\partial U}{\partial X}+\frac{\partial}{\partial Y}\Gamma\frac{\partial V}{\partial X}-U\left\{\frac{\Gamma}{K/\varepsilon}+\frac{C_F}{(K/\varepsilon)^{1/2}}\left(U^2+V^2\right)^{1/2}\right\}$
y-momentum	$-\varepsilon^{+2}\frac{\partial P}{\partial Y}+\frac{\partial}{\partial X}\Gamma\frac{\partial U}{\partial Y}+\frac{\partial}{\partial Y}\Gamma\frac{\partial U}{\partial Y}+\varepsilon^{+2}\frac{Gr}{Re^2}T-V\left\{\frac{\Gamma}{K/\varepsilon}+\frac{C_F}{(K/\varepsilon)^{1/2}}\left(U^2+V^2\right)^{1/2}\right\}$

Table 2 Validation of results.

Porosity	Gr	Haghshenas et al. [29]	Present study	% deviation
$\varepsilon = 0.4$	$Gr = 10^4$	1.541	1.498	2.7
	$Gr = 10^5$	4.294	4.010	6.5
	$Gr = 10^6$	9.432	8.86	6.0
$\varepsilon = 0.6$	$Gr = 10^4$	1.731	1.689	2.4
	$Gr = 10^5$	5.032	4.867	3.2
	$Gr = 10^6$	11.211	10.631	5.1

medium filling a lid-driven square enclosure for both non-uniform and uniform heating. They found that low values but almost uniform local Nusselt numbers for low Peclet numbers. They found also, for high Peclet numbers at $Da = 10^{-3}$, localized enhancement for heat transfer rates. Other related studies on natural convection or mixed convection heat transfer and fluid flow under different boundary conditions can be found in refs.

In this study, the case is such that one vertical side of an open sided cavity moves and the cavity has a partial heater. The novelty of the present work that it presents the application of a moving lid heated cavity with open sided filled partially with porous media. Different governing parameters were analyzed to investigate their effects on heat and fluid flow in the case described.

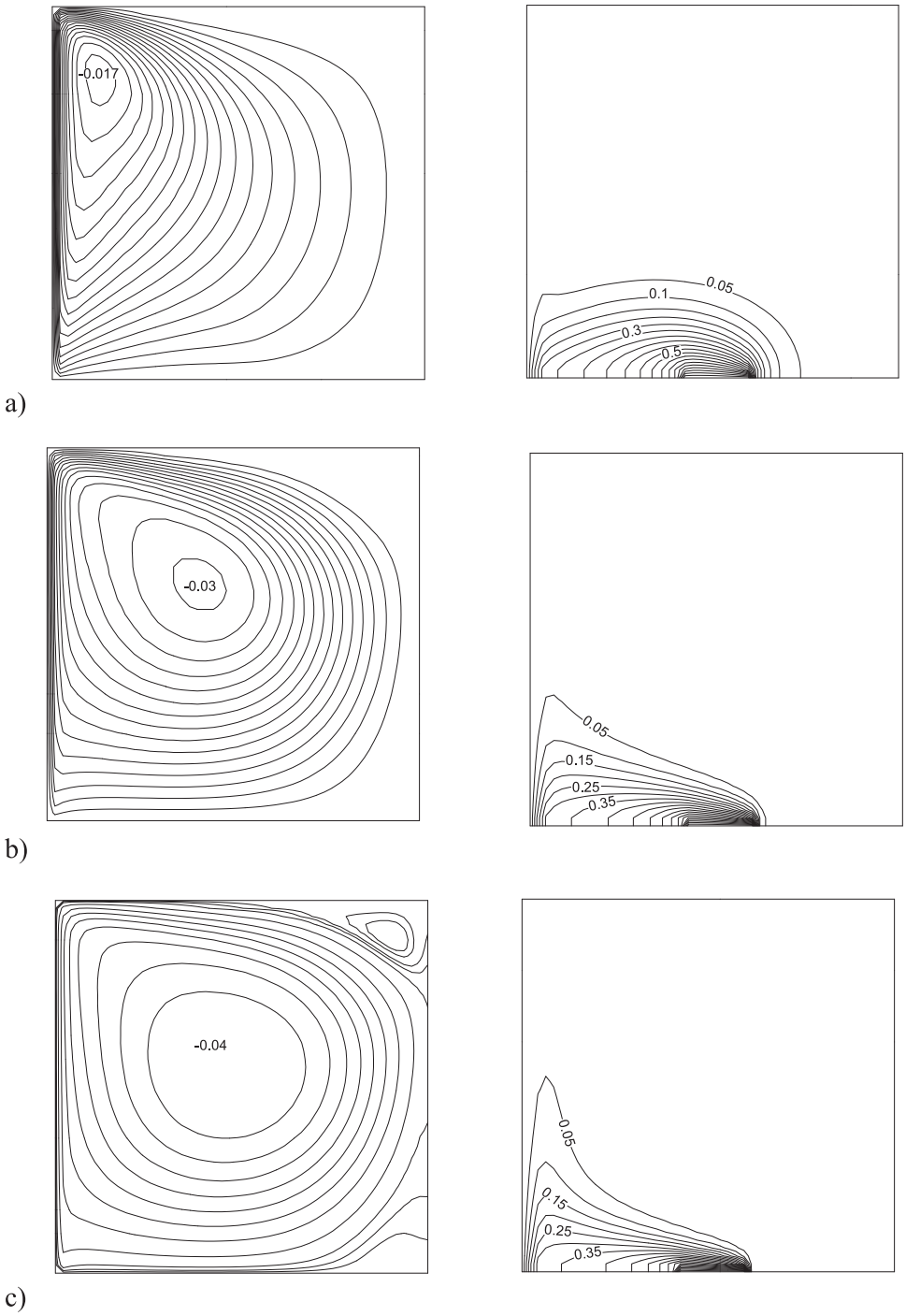

Fig. 2 Streamlines (on the left) and isotherms (on the right) for different Darcy numbers, $Re = 1000$, $Gr = 10^5$, $x_L/L = 1/5$ and $c/H = 1/5$, (a) $Da = 0.001$, (b) $Da = 0.01$, (c) $Da = 0.1$.

2. Physical model

Fig. 1 shows the complte model of the two-dimensional flow model along with the coordinates and the boundary conditions. The eclusure is a square one with the length$L = H$. In addition it moves with constant velocity, the top wall of the cavity has isothermal boundary conditions with temperature lower than the corners's heater temperature. The lengths of

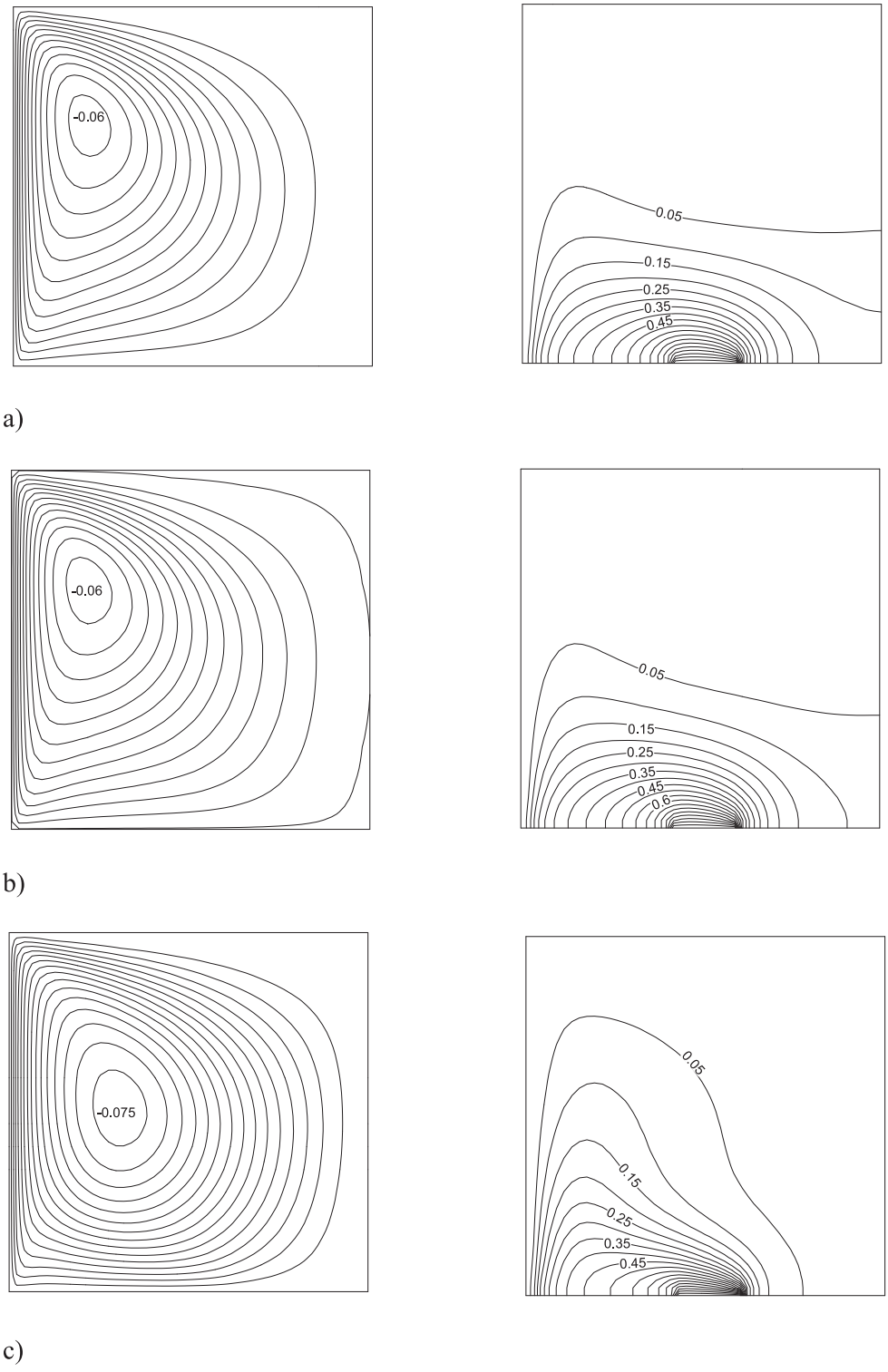

Fig. 3 Streamlines (on the left) and isotherms (on the right) for different Darcy numbers, $Re = 100$, $Da = 0.01$, $x_L/L = 1/5$ and $c/H = 1/5$, (a) $Gr = 10^3$, (b) $Gr = 10^4$, (c) $Gr = 10^5$.

the isothermal boundaries of the corner heater in the horizontal and vertical directions are XH and YH, respectively.

3. Governing equations

Assumptions can be listed as

- The walls are impermeable and adiabatic.
- It is valid to use Boussinesq approximation.
- Radiation is neglected compared to other heat transfer modes.
- The gravity acts towards the earth's ceter (−y direction).

The following is the governing equation in dimentional form [9]:

$$\frac{\partial}{\partial X}\left(U\phi - \Gamma\frac{\partial \phi}{\partial X}\right) + \frac{\partial}{\partial Y}\left(V\phi - \Gamma\frac{\partial \phi}{\partial Y}\right) = S \tag{1}$$

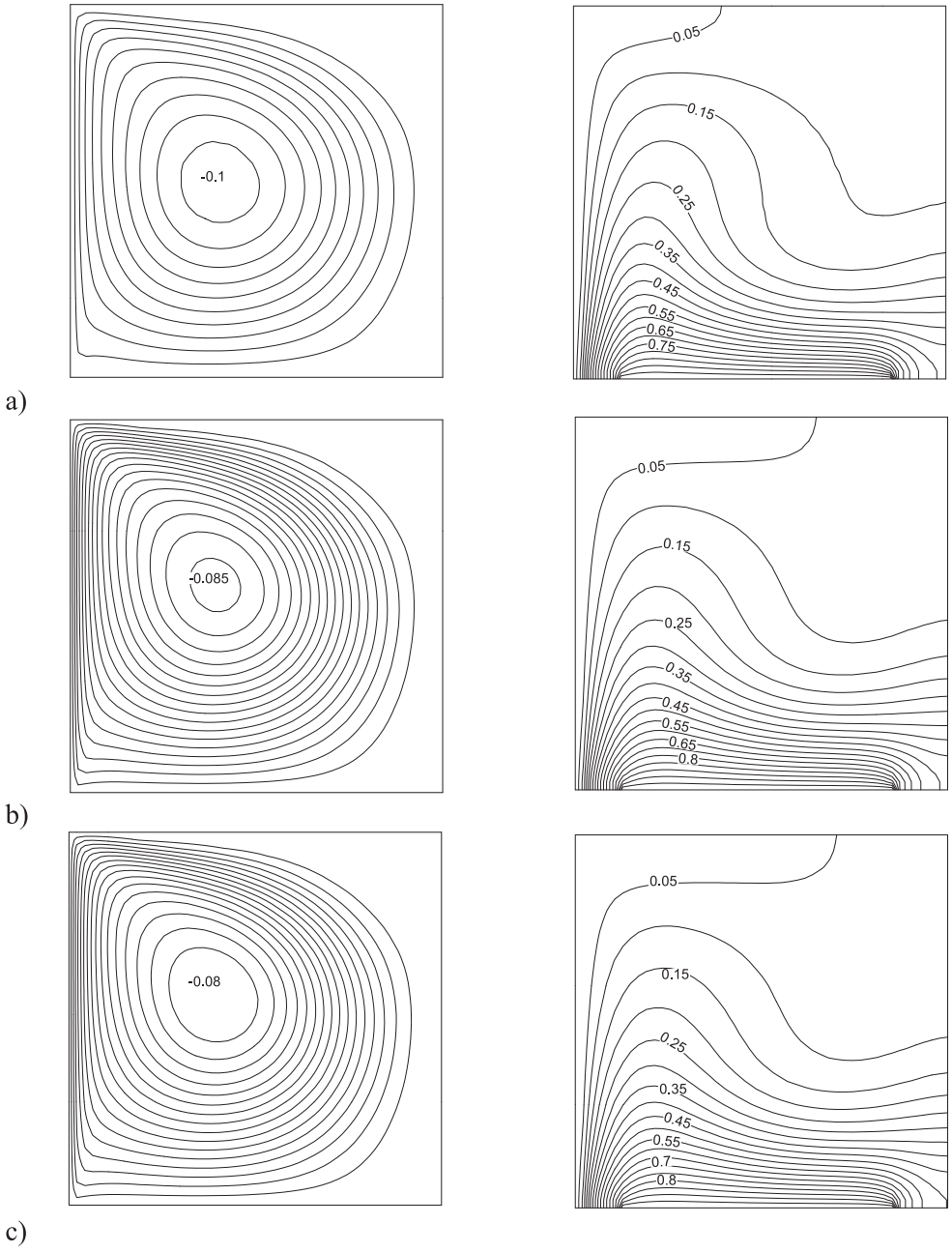

Fig. 4 Streamlines (on the left) and isotherms (on the right) for different Darcy numbers, $Da = 0.1$, $Re = 1000$, $Gr = 10^5$, $x_L/L = 1/5$ and $c/H = 1/5$, (a) $Gr = 10^5$, (b) $Gr = 10^4$, (c) $Gr = 10^{3.}$

Source term S is given in Table 1. Dimensionless parameters are also given as follows:

$$X=\frac{x'}{H},\quad Y=\frac{y'}{H},\quad U=\frac{u'}{V_{lid}},\quad V=\frac{v'}{V_{lid}},\quad P=\frac{p'}{\rho V_{lid}^2},\quad \Theta=\frac{T'-T_c}{T_h-T_c},$$
$$Da=\frac{K}{H^2},\quad Gr=\frac{CK^{3/2}g\beta\Delta TH^3}{\nu^2},\quad Re=\frac{V_{lid}H}{V},\quad Ri=\frac{Gr}{Re^2},\quad \mathrm{Pr}=\frac{V}{\alpha} \tag{2}$$

3.1. Boundary conditions

The boundary conditions in this study are shown on the physical model of the geometry as in Fig. 1. The solid walls' boundary conditions were no-slip. A 0.9 porosity (ε) was assumed. The pertinent boundary conditions are given as follows

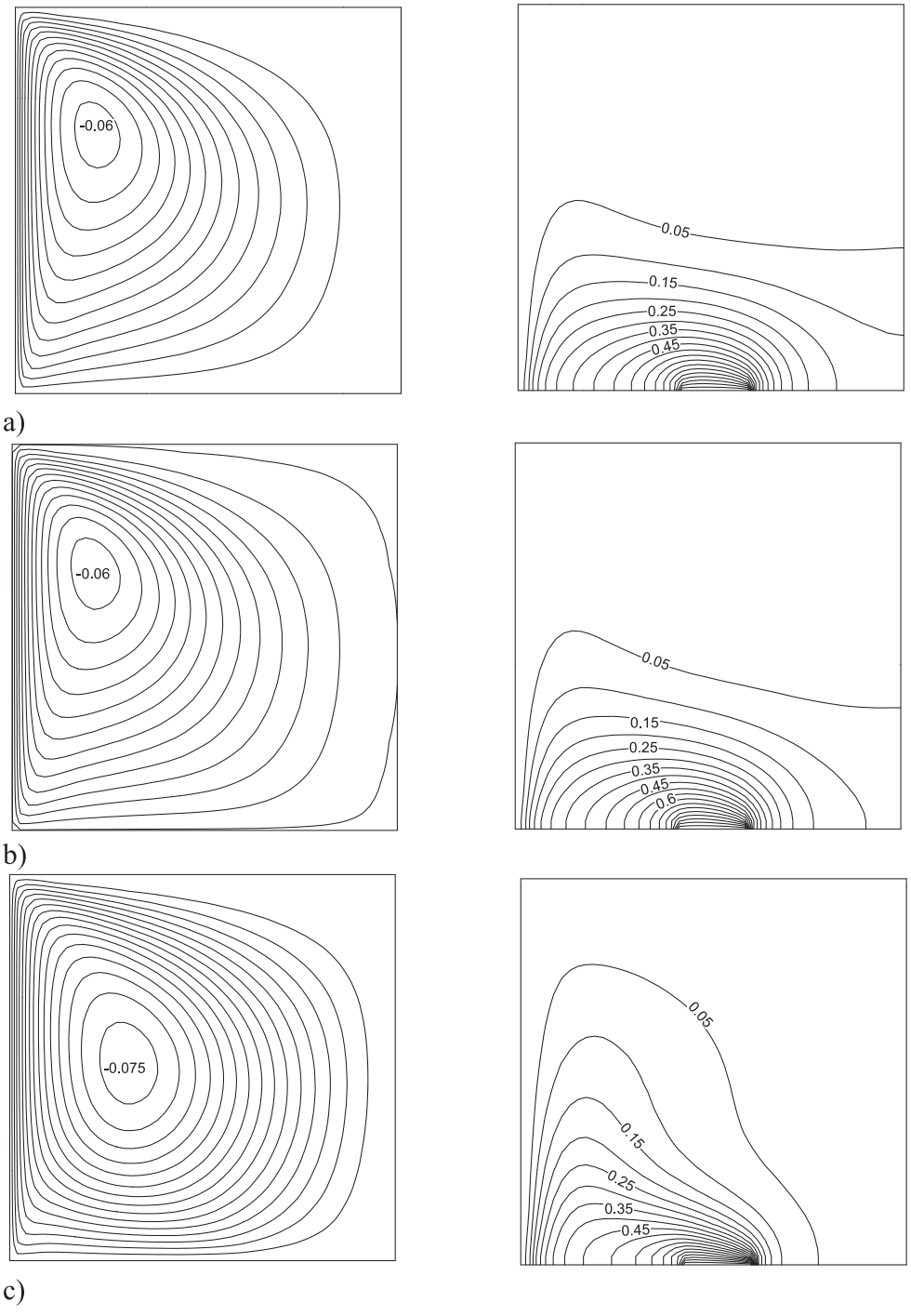

Fig. 5 Streamlines (on the left) and isotherms (on the right) for different Darcy numbers, $Re = 100$, $Da = 0.01$, w/L = 1/5 and c/H = 1/5, (a) $Gr = 10^3$, (b) $Gr = 10^4$, (c) $Gr = 10^5$.

at top wall : $Y = H, \quad 0 < X < L, \quad U = V = 0, \quad \dfrac{\partial \Theta}{\partial Y} = 0$ (3a)

at bottom wall $Y = 0, \quad 0 \leqslant X \leqslant L, \quad U = V = 0, \quad \dfrac{\partial \Theta}{\partial Y} = 0$ (3b)

along the heater $\Theta = 1$ (3c)

at left wall $X = 0, \quad 0 \leqslant Y \leqslant H, \quad U = \Theta = 0, \quad V = 1$ (3d)

at right wall $X = L, \quad 0 \leqslant Y \leqslant H, \quad \dfrac{\partial U}{\partial X} = \dfrac{\partial V}{\partial X} = \dfrac{\partial \Theta}{\partial X} = 0$ (3e)

The local Nusselt Nu_x and average Nusselt numbers are the physical quantities of interest. They are calculated along the hot wall as

$$Nu_x = -\left(\frac{\partial \Theta}{\partial y}\right)_{X=w} \tag{4}$$

$$\overline{Nu} = \int_{w=0}^{w} Nu_x dy \tag{5}$$

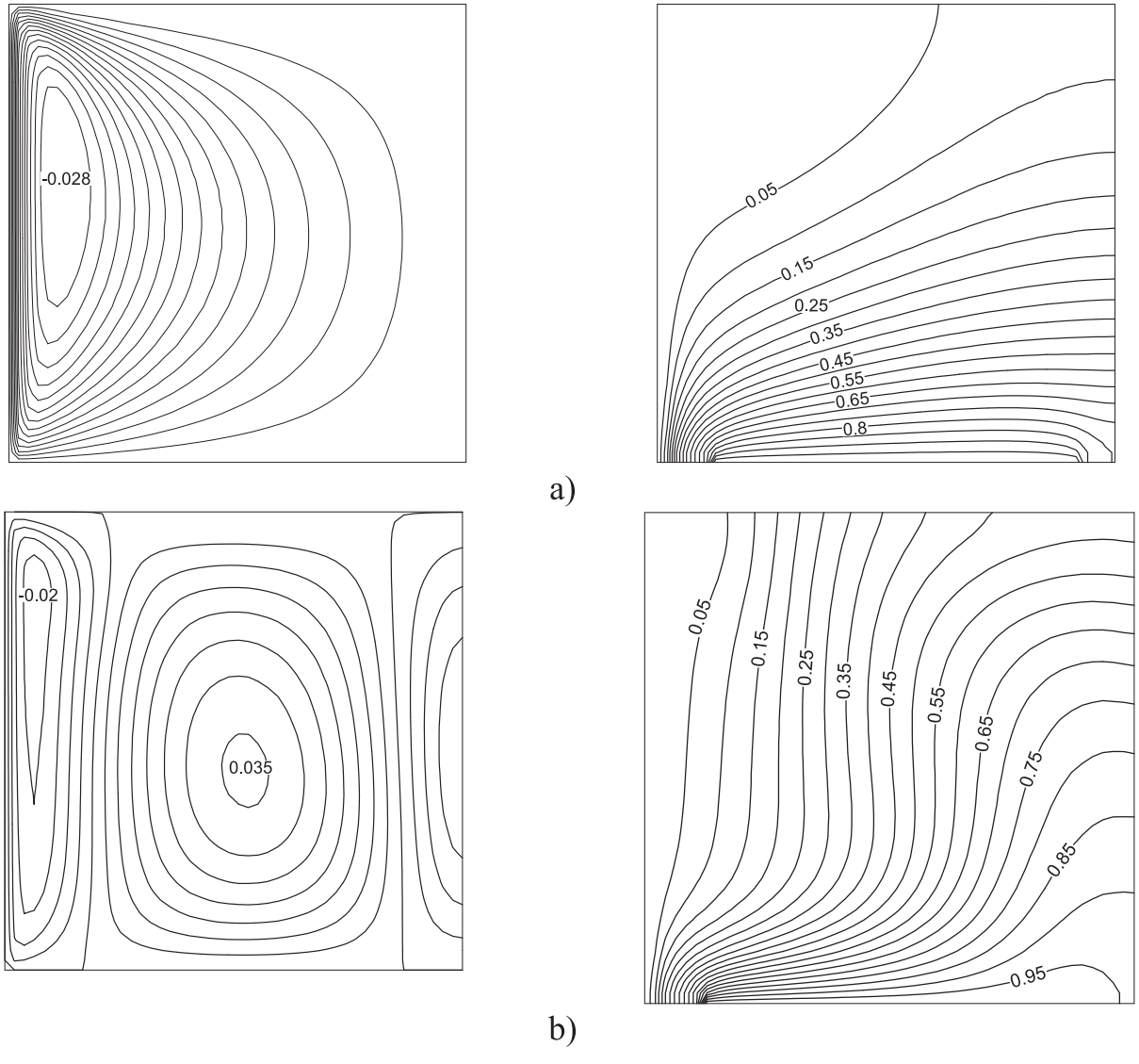

Fig. 6 Streamlines (on the left) and isotherms (on the right) for different Darcy numbers, $Re = 100$, $Da = 0.001$, w/L = 4/5 and c/H = 0.5, (a) $Gr = 10^3$, (b) $Gr = 10^5$.

3.2. Validation and grid test

A test was performed and the results obtained were used to validate the code with those found in litrerature. The obtained results are shown in Table 2. There was a good agreement between the Haghshenas et al. [33] results and the present test results. The authors are not aware of any related experimental data for comparison with the numerical results shown in Table 3 and Table 4. Other validation results for the studied code can be found in refs. [9,18,51-36]. Fig. 1 (b) and Table 5 show the qualitative validation from refs. [37,38]. The comparison shows that the results are acceptable.

In order to solve the governing equation, an arrangement of staggered grid was used in the finite difference method that is based on finite volume. Nakayama [28] proposed a modified version of the general purpose of SAINTS code which was used with SIMPLE algorithm [27]. The SAINTS stands to an integration of turbulence and porous media simulator with Navier–Stokes equation. A hybrid of upwind schemes and the central difference was used for the diffusive and convective terms. The TDMA method was used to solve the linear algebraic equation. The definition of the stream function was used to calculate it as $u = \partial\psi/\partial y$, $v = \partial\psi/\partial x$. To obtain a solution's stable convergence of v-velocity, u-velocity, pressure and energy equations, an under-relaxation parameter of 0.3, 0.3, 0.2 and 0.5 were used. In the computational solution, grids dimension tested were 24 × 24, 36 × 36 and 48 × 48. Based on the results obtained, the 48x48 dimension was chosen for the meshing the grid. Next to the boundaries, fine grids were used in the mesh.

Satisfying the following condition was used to terminate the iteration process:

$$\sum_{ii} \left|\Phi_{ij}^{m} - \Phi_{ij}^{m-1}\right| / \sum_{ii} \left|\Phi_{ij}^{m}\right| < 10^{-5} \tag{6}$$

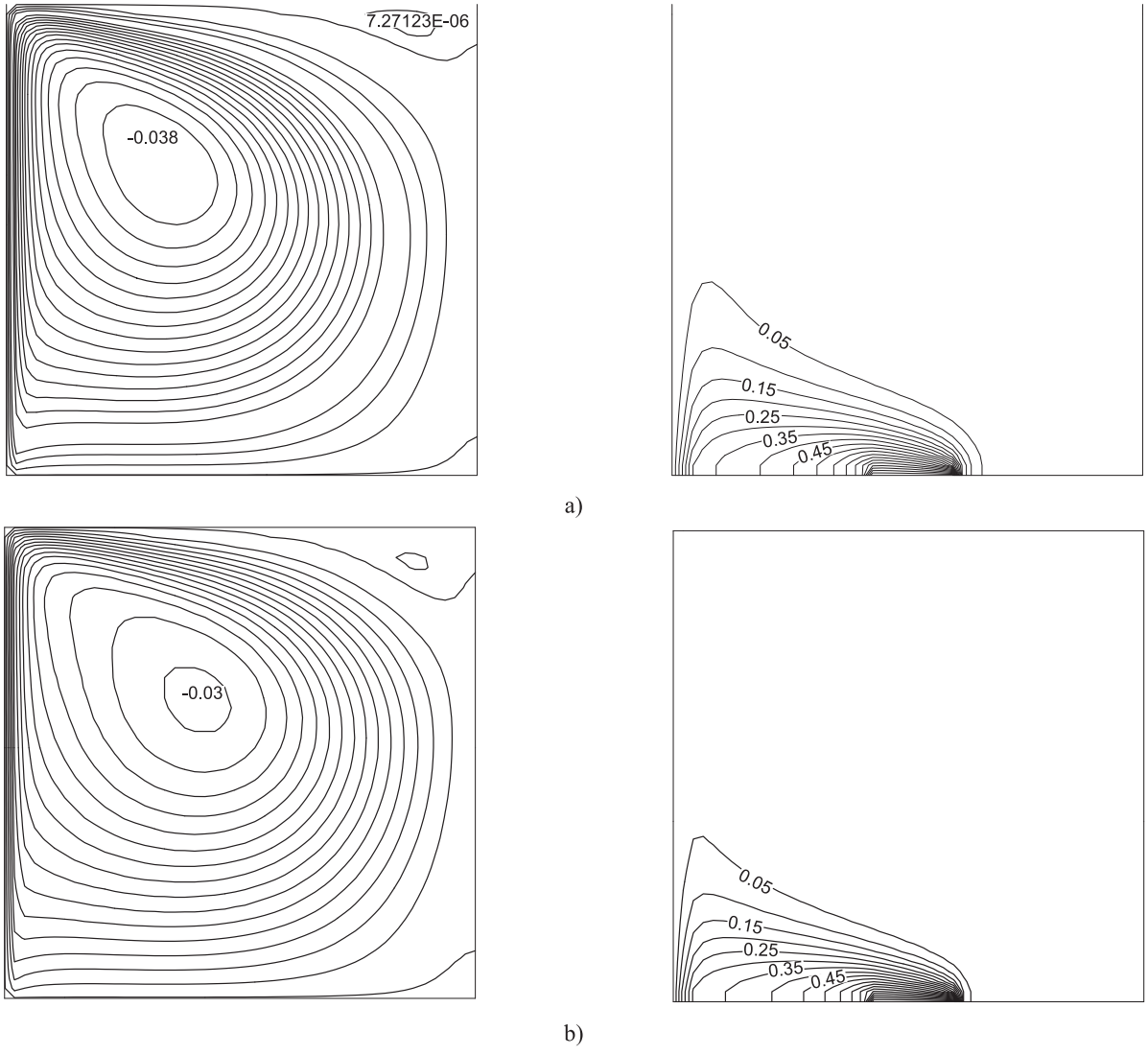

Fig. 7 Streamlines (on the left) and isotherms (on the right) for different Reynolds numbers, $Da = 0.001$, c/H = 0.5 and w/L = 1/5, $Gr = 10^{5,}$ (a) $Re = 500$, (b) $Re = 1000$.

where U stands for either V, U, P or dimensionless temperature and m implies the iteration step.

4. Results and discussion

This computational work of a partially heated porous media filled open cavity with left side moving wall at different parameters as length of partial heating ($1/5 \leq w/L \leq 1$), ($0.3 \leq c/L \leq 0.7$) location of heater, Grashof numbers ($10^3 \leq Gr \leq 10^5$), Reynolds number ($100 \leq Re \leq 1000$) and Darcy number ($0.001 \leq Da \leq 0.1$). Based on these parameters, the results will be presented as isotherms, streamlines, mean and local Nusselt numbers, temperature variations and velocity distribution. For higher Grashof number such as $Gr = 10^6$, the code did not work due to oscillation or transition to turbulent. Thus, the results are presented for lower than this value for safety in all cases.

Fig. 2 shows the isotherms (on the right) and the streamlines (on the left) for different Darcy numbers at $Re = 1000$, $Gr = 10^5$, $w/L = 1/5$ and $c/H = 0.5$. A clockwise circulation cell is formed for all Darcy numbers except $Da = 0.1$. A formatrion of small circulation cell nearby the right top side based on stream function values was noticed; flow strength increased with increasing Darcy numbers. The center of main cell moves diagonally with increasing of Darcy number. Its shape is also a function of Darcy number. Fig. 3 shows isotherms (on the right) and streamlines (on the left) for parameters of $Re = 100$, $Da = 0.01$, $w/L = 1/5$ and $c/H = 0.5$ at different Grashof numbers. Both temperature distribution and flow field are not affected at lower Grashof numbers because of the conduction mode dominates the other modes of heat transfer. On the contrary, as seen from isotherms which are presented in right column, conduction mode turns to be prevailing at lower values of Grashof number. For $Ri = 1$ ($Ri = Gr/Re^2$), most of

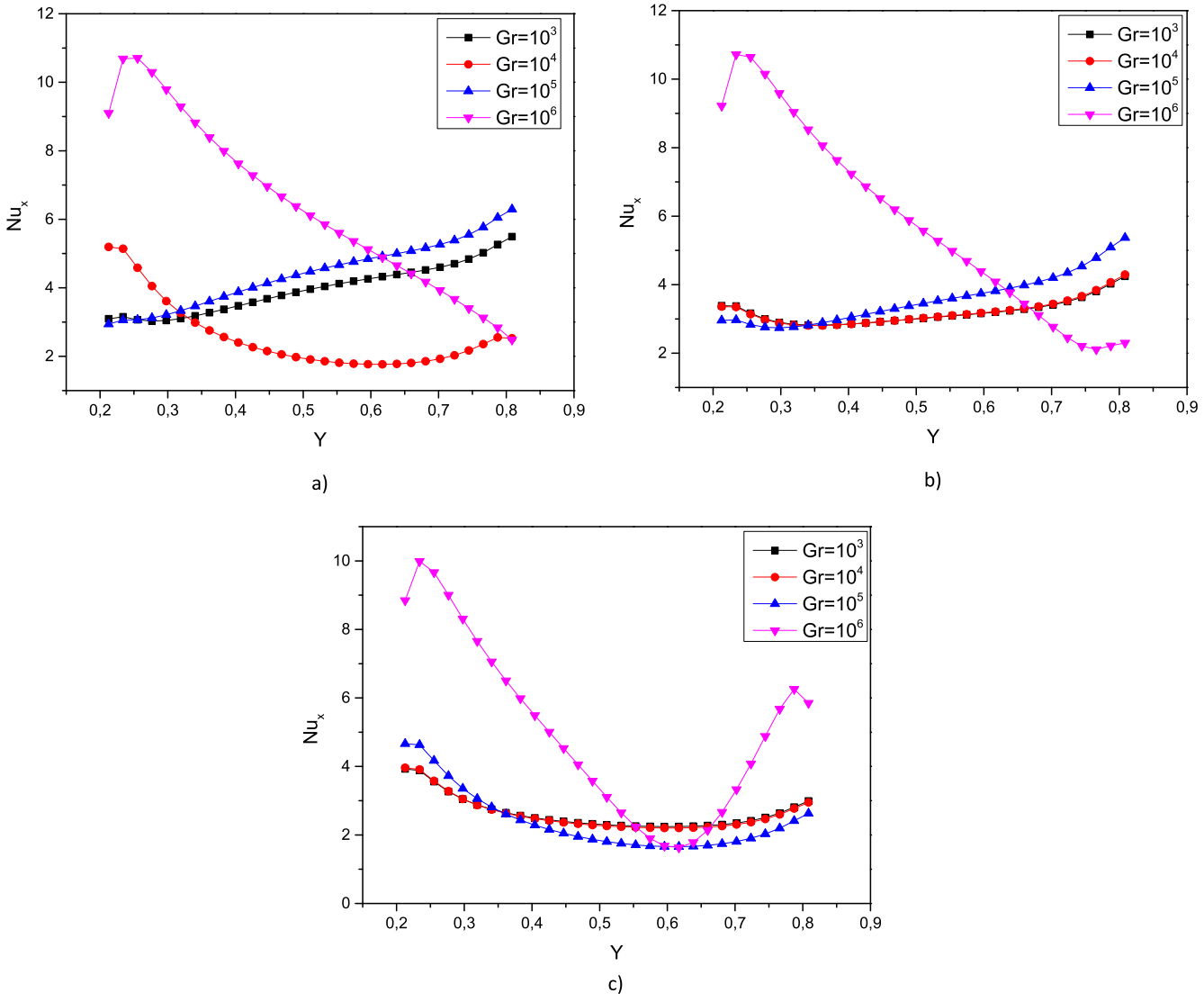

Fig. 8 Variation of local Nusselt number along the heater for different Grashof numbers at $Re = 100$, $c/H = 0.5$ and $w/L = 1/5$, (a) $Da = 0.1$, (b) $Da = 0.01$, (c) $Da = 0.001$.

the fluid becomes same temperature and little plume is observed near the moving lid as seen from Fig. 3(b). As shown in Fig. 3(c), as Grashof number increases natural convection becomes dominant. Fig. 4 illustrates the isotherms (on the right) and streamlines (on the left) for different Grashof numbers and parameters of $Da = 0.1$, $Re = 1000$, $Gr = 10^5$, w/L = 1/5 and c/H = 0.5. As seen from the figures, single circulation cell is formed inside the cavity with clockwise direction. Flow strength decreases with decreasing Grashof number. Comparison of other figure shows that higher flow strenght is formed with the increasing of Reynolds number.

Fig. 5 shows the isotherms and streamlines for different values of Grashof numbers. As seen from the figure, variation of Grashof number for $Gr = 10^3$ and 10^4, temperature distribution and flow field become almost same due to conduction mode of heat transfer. The isotherms move towward to moving lid due to moving flow. Completely different flow field and isotherms distribution is observed inside the cavity for $x_L/L = 4/5$ and c/H = 0.5 as seen in Fig. 6. At the lowest value of Grashof number, isotherms are nearly parallel to the heater caused by the domination of conduction mode. However, multiple cells are formed inside the cavity with increasing of Grashof numbers. A cell elongated with vertical wall and that turns in clockwise direction and counterclockwise circulation is formed at the middle of the cavity. Isotherms are nearly parallel to vertical walls. Effects of Reynolds number can be seen on fluid flow and heat for the parameters with $Da = 0.001$, w/L = 1/5 and c/H = 0.5, $Gr = 10^5$ in Fig. 7. For higher Reynolds number, namely, lower Richardson number, $Ri = Gr/Re^2$, forced convection becomes effective inside the cavity and a small circulating cell is formed near the right top side of the cavity. The thermal boundary layer's thickness decreases as a result of increasing of Reynolds number but there is no big difference for

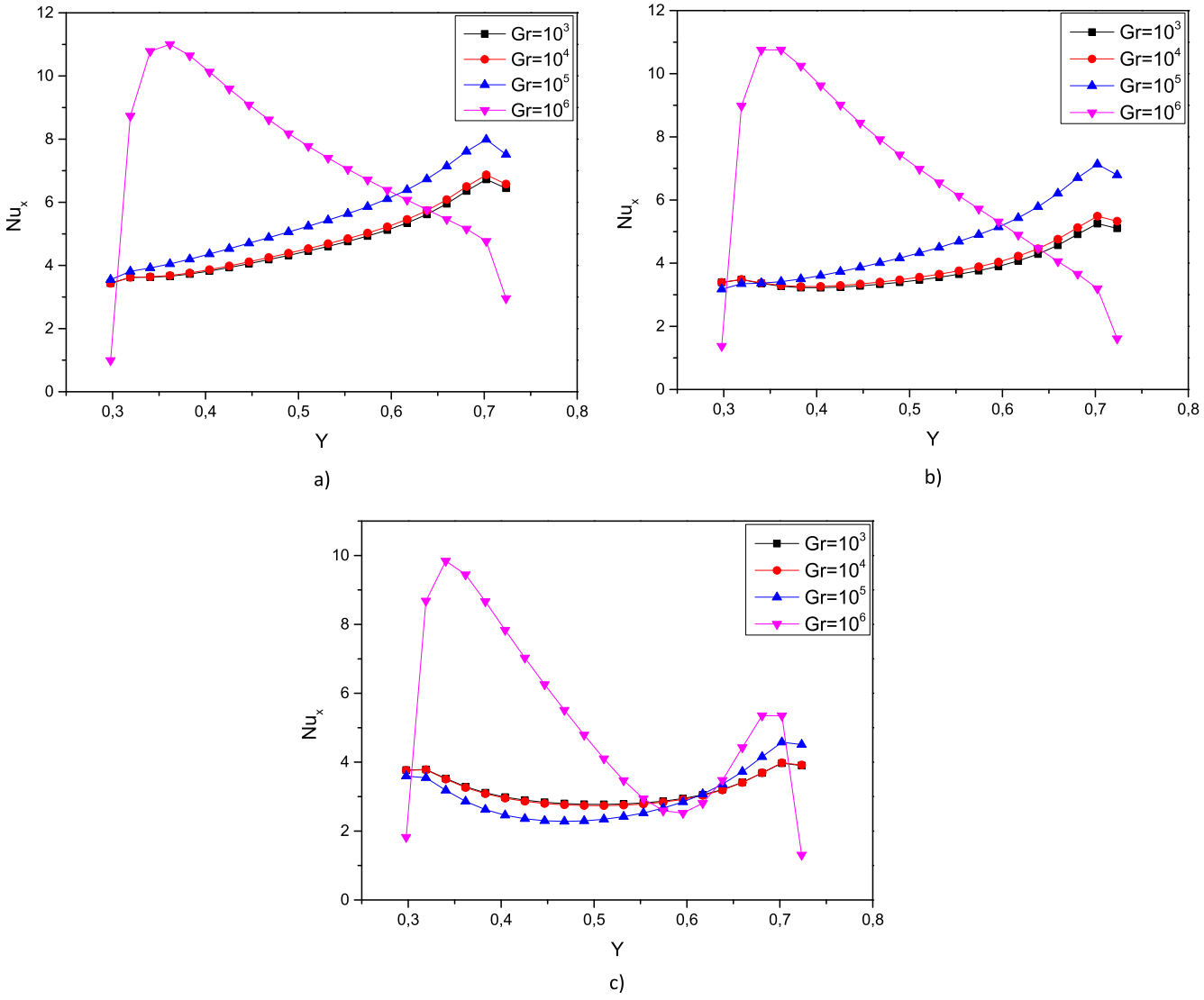

Fig. 9 Variation of local Nusselt number along the heater for different Grashof numbers at $Re = 100$, c/H = 0.5 and w/L = 2/5, (a) $Da = 0.1$, (b) $Da = 0.01$, (c) $Da = 0.001$.

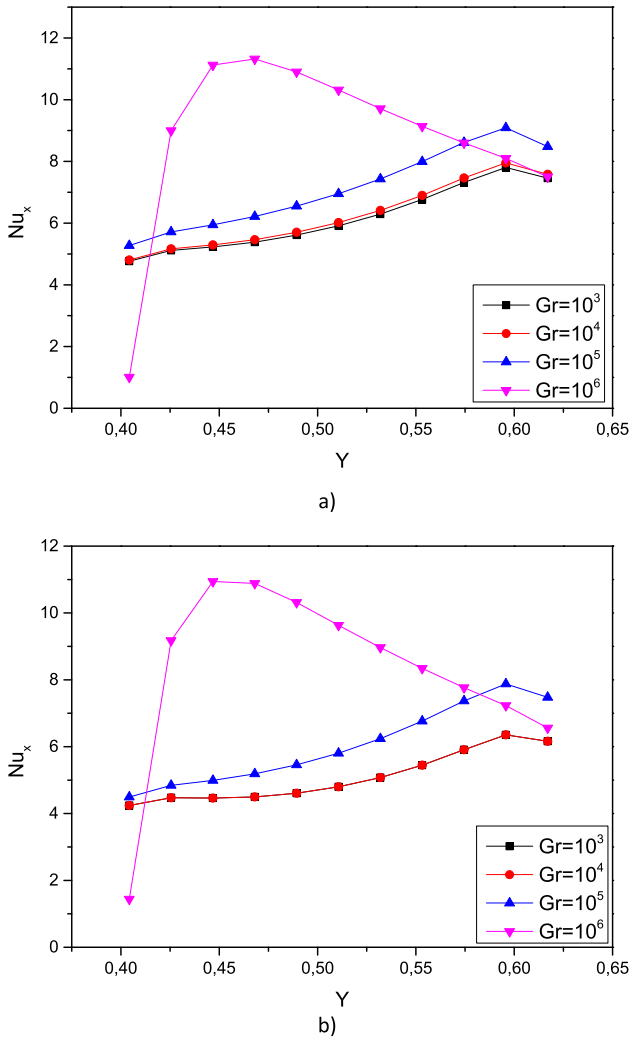

Fig. 10 Variation of local Nusselt number along the heater for different Grashof numbers at $Re = 100$, h/H = 0.5 and w/L = 3/5 (a) $Da = 0.1$, (b) $Da = 0.01$.

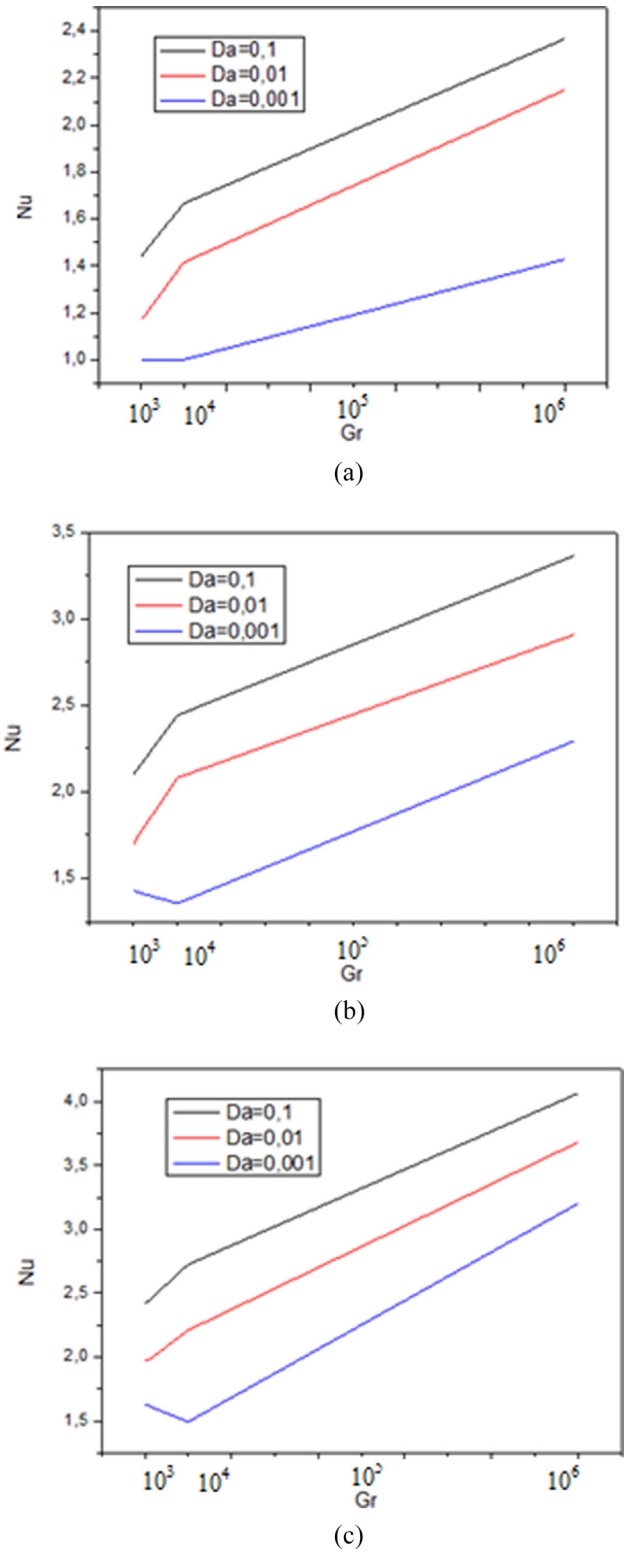

Fig. 11 Variation of mean Nusselt number for different parameters, (a) w/L = 1/5, (b) w/L = 2/5, (c) w/L = 4/5.

$Re = 500$ and 1000 on flow field. It means that almost similar results can be obtained for further Reynolds number due to domination of forced convection mode of heat transfer. Variation of local Nusselt number are presented in Fig. 8 for $Re = 100$, w/L = 1/5 and c/H = 0.5 at different values of Darcy numbers and Grashof numbers. As seen from the variation of values, heat transfer becomes maximum for $Gr = 10^6$ because of the convection mode domination for $Da = 0.1$. But it declines with increasing the heater length. When, conduction mode of heat transfer becomes dominant, namely, lower values of Grashof number, heat transfer increases along the heater. For this results, local Nusselt number shows a different behavior for $Gr = 10^4$, namely, it shows a minimal values around Y = 0.6. Heat transfer decreases as Darcy numbers decrease. For the highest value of Darcy number, U-shaped distribution is observed for $Gr = 10^6$.

Fig. 9 presents the variation of local Nusselt number for $Re = 100$, w/L = 2/5 and c/H = 0.5 at different Grashof numbers and Darcy numbers. As seen from the figure, there is a maximum value for $Gr = 10^6$ around X = 0.35. Other values of Grashof numbers, local Nusselt numbers are increased along the heater at $Da = 0.1$. Results are very similar for $Da = 0.01$ and variation of local Nusselt numbers exhi-

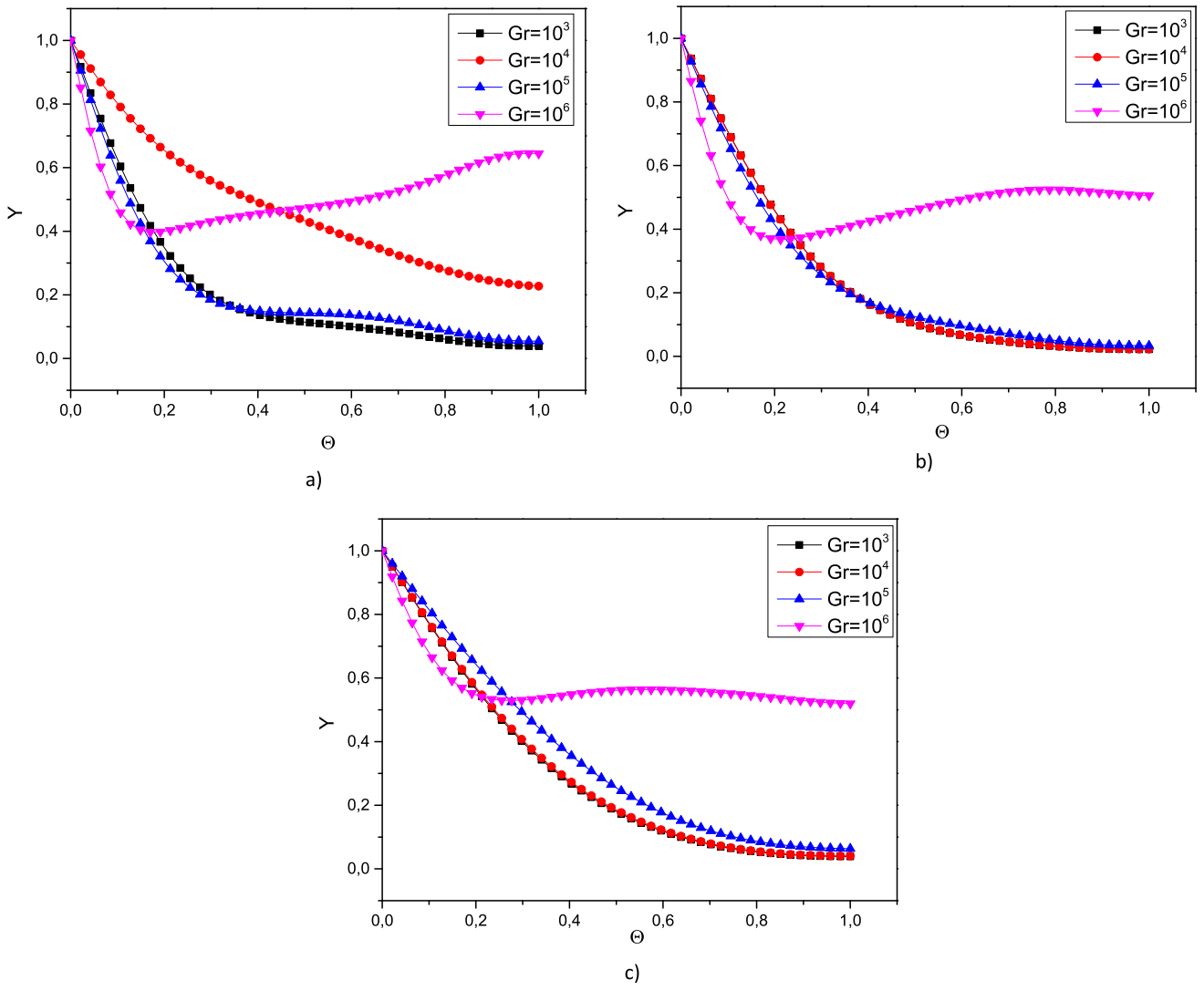

Fig. 12 Variation of temperature profile at the middle of the cavity for different Grashof numbers at $Re = 100$, c/H = 0.5 and w/L = (a) $Da = 0.1$, (b) $Da = 0.01$, (c) $Da = 0.001$.

bit same trends. On the contrary, sinewave shaped distribution is obtained for $Gr = 10^6$ but there is almost constant variation is formed for remaining values of Grashof numbers.

The Fig. 10 shows the variation of local Nusselt numbers for different parameters. As seen from the figure, variation of local Nusselt numbers exhibit similar trends for all values of Darcy numbers but their values are decreased with decreasing of Darcy numbers. Fig. 11 illustrates the variation of mean Nusselt number at different length of heater and different governing parameters such as Grashof and Darcy numbers. As seen from the result that there is a linear increasing with Grashof number and Variation of temperature profile along the heater for different Grashof numbers at different Darcy numbers and $Re = 100$, c/H = 0.5 and w/L = 3/5 is presented in Fig. 12. The trends of temperature profiles give very similar result for $Ra \leq 10^5$. On the contrary, convection heat transfer is occurred for $Ra = 10^6$ and there is a minimal point around $Y = 0.4$ and 0.5 depending on the Darcy number. It is shown that temperature values of minimum point for $Ra = 10^6$ is decreased with decreasing of Darcy number. In similar way, Fig. 13 illustrates the variation of temperature profile at the middle of the cavity for different Grashof numbers and Darcy numbers for $Re = 100$, c/H = 0.5 and w/L = 2/5. Fig. 14 illustrates the variation of temperature with the same parameters of Fig. 13 but for the highest value of heater length. As seen clearly from the figure, temperature values are decreased from the heater to top side of the cavity. When the Grashof number is at its highest value, the curve is more parallel to moving lid which shows the heat transfer's convection mode domination.

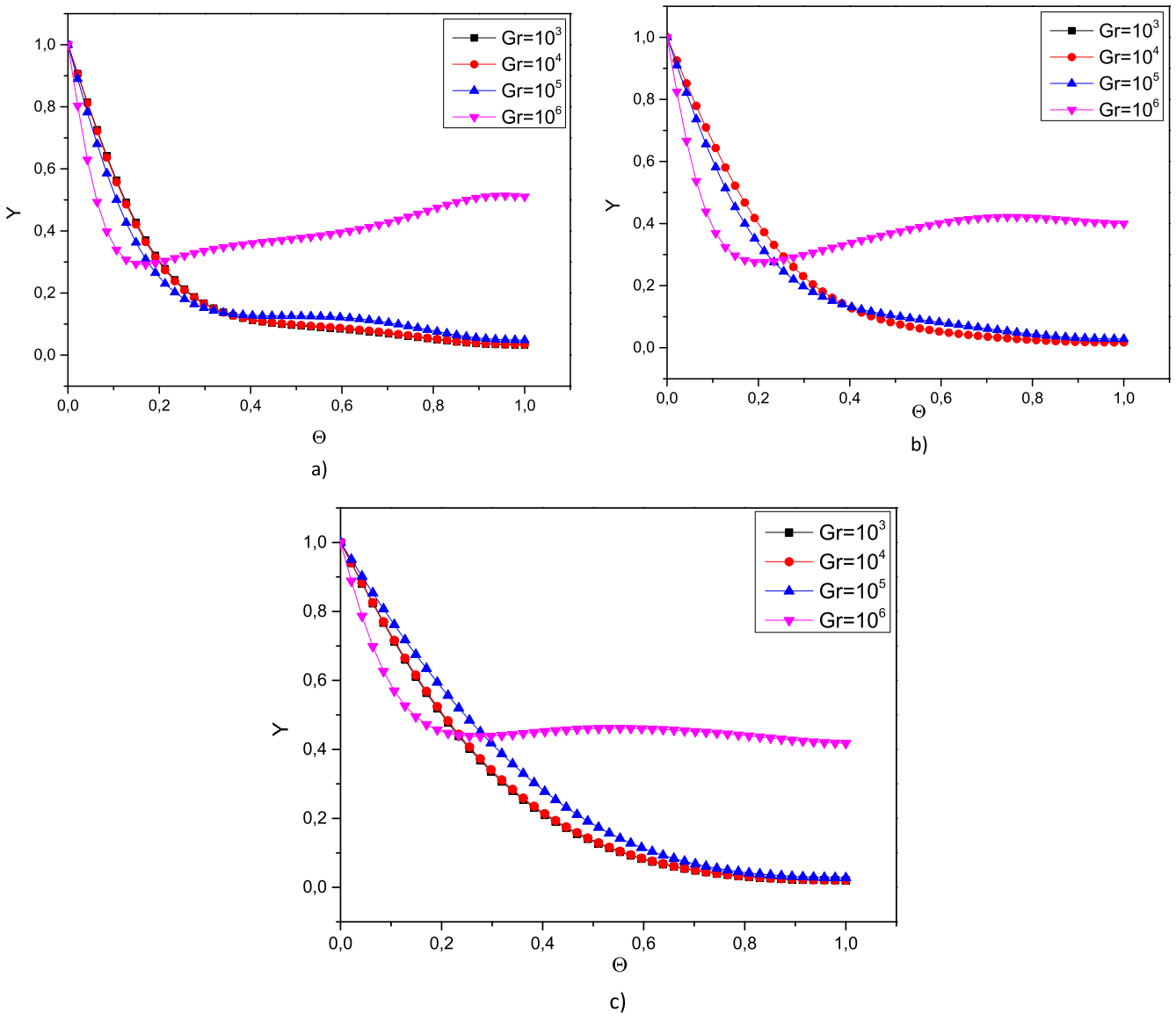

Fig. 13 Variation of temperature profile at the middle of the cavity for different Grashof numbers at $Re = 100$, h/H = 0.5 and w/L = 2/5 (a) $Da = 0.1$, (b) $Da = 0.01$, (c) $Da = 0.001$.

5. Conclusions

A computational work has been performed to investigate the mixed convection in a partially heated lid-driven porous media filled enclosure with one side opening and partial heating. It is clearly seen from the obtained result that flow field and temperature distribution inside the cavity is really complex due to both moving lid and opening side of the cavity. Also, another force comes from the partial heater. Convection mode of heat transfer becomes stronger for higher values of Grashof number and increasing of heater length.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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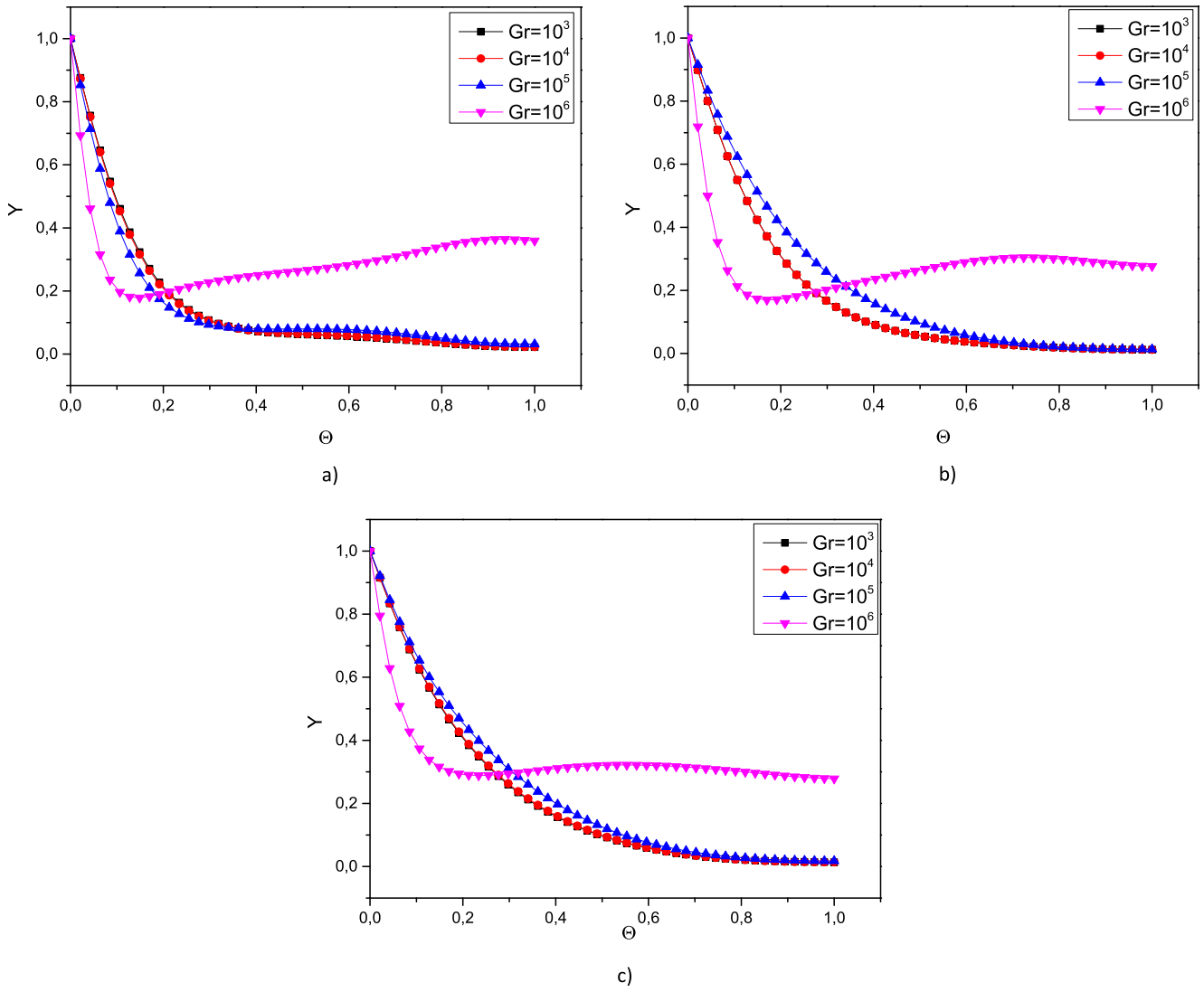

Fig. 14 Variation of temperature profile at the middle of the cavity for different Grashof numbers at $Re = 100$, h/H = 0.5 and w/L = 3/5 (a) $Da = 0.1$, (b) $Da = 0.01$, (c) $Da = 0.001$.

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