Natural Convection within Differentially Heated Square Enclosure with Partitions

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The study of heat transfer in enclosures and partitioned enclosures is an important field of research for the scientists and researchers. In the present work, investigation of the natural convection in partitioned enclosure and its control by suitably choosing the location and size of the partition has been done. The properties of the working medium, ie, air was considered as constant. The variation of the density was considered as per the Boussinesq approximation. The SIMPLE algorithm was employed to solve the N-S equation and energy equation and FEM was employed as the numerical technique. The presence of partition influences considerably the flow phenomenon and consequently the energy transfer, which were analyzed through isotherm and streamline pattern.

Keywords : Differentially heated square enclosure; SIMPLE algorithm; Isotherm and streamline patterns

NOTATION

d : distance of partition from left wall, m

g : acceleration due to gravity, m/s^2

Gr : Grashoff number $[\beta_g(T_h - T_c)H^3/\nu^2]$

H : enclosure height, m

h : partition height,m

k_f : thermal conductivity at T_f, W/m-K

P$_r$: Prandtl number ($Pr = \frac{\mu c_P}{k}$)

R$_a$: Rayleigh number (Gr Pr)

R$_e$: Reynold's number ($R_e = \frac{\rho U_\infty H}{\mu}$)

T : temperature, K

T_f : mean temperature = $(T_h + T_c)/2$, K

T_h, T_c : temperature of hot wall and cold wall, K

u, v : x and y velocity components, m/s

w : partition width, m

β : volumetric expansion co-efficient, K^{-1}

ν : kinematic viscosity, m^2/s

ρ : density, kg/m^3

* : non-dimensional form

0 : reference state

INTRODUCTION

The study of heat transfer in enclosures and partitioned enclosures is important in the design of various thermal systems, such as, building components for energy conservation, nuclear reactor cooling and so on.

Various works have been carried out a finite difference numerical study of a square enclosure containing air for two different configurations of an incomplete partition inside the enclosure[1]. The study pointed out that the finite thickness and thermal conductivity of the partition significantly affect the heat transfer in enclosures having full length vertical partitions. Even it has been studied about the laminar natural convection and conduction in enclosures filled with air having multiple vertical partitions with finite thickness and conductivity using a finite difference solution procedure[2]. The study covered the Rayleigh number range within 10^3 to 10^7 and aspect ratio within 5 to 20 apart from different spacing of the partition. The ratio of the thickness of the partition to the width of enclosure was varied from 0.01 to 0.1. The number of partitions were varied from one to five. However, no correlation was reported in the study. The research works carried out a similar numerical study for an inclined enclosure filled with air and provided a correlation for convective Nusselt number[3]. Previously works were done to consider the effects of interaction of surface radiation among the enclosure walls and partition[4]. Two-dimensional finite difference modelling based on a control volume formulation was adopted to study the interaction between laminar free convection ($4.54 \times 10^4 \leq R_a \leq 1.2 \times 10^6$) and surface radiation in a partitioned tall enclosure using air as the medium. The partition was assumed to be very thin and perfectly conducting. The effect

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of an off-centered partition was also studied. For the case of tall enclosures, the aspect ratio was varied from 2 to 35. Both studies were carried out for a range of emissivity values from 0.05 to 0.95. A detailed parametric study has resulted in correlations for convective and radiative Nusselt numbers. The result of previous researchers has shown that the reduction[4] of Nusselt number by factor of $(n+1)^a$, where n is the number of partition and a, the fixed quantity, which is not always true for all situations in enclosures having walls with non-zero emissivity. It was also studied numerically[5] radiation natural convection interaction in two-dimensional complex enclosures and was observed a decrease in average Nusselt number with increasing partition height.

Earlier studies have concluded that the Nusselt number in a partition enclosure[6,7] is reduced by a factor of $(n+1)^a$ where, $a = -0.61$ and $a = -1$, when compared to the Nusselt number obtained for a non-partition enclosure. The researchers presented an experimental investigation of the heat transfer results of the partitioned enclosure subjected to coupled natural convection and surface radiation[8]. Earlier the scientists have studied the effect of a heat conducting vertical partition in an enclosure on natural convection heat transfer and fluid flow using the polynomial-based differential quadrature (PDQ) method[9]. The average heat transfer rate exhibits little dependence on the width of the partition in the range taken into consideration in this research for the thickness of the partition[9]. The researchers have considered steady, laminar, natural convective flow of a viscous fluid in an inclined enclosure with partitions[10]. The problem has been formulated in terms of vorticity-stream function procedure. A numerical solution based on the finite volume method was obtained. Results for the average Nusselt number at the heated wall of the enclosure and the difference of extreme stream-function values are presented and discussed for various Rayleigh numbers, inclination angles and dimensionless partition heights.

The control of natural convection by suitably deciding the geometry of partition within the enclosure was the objective of present study. The vertical walls of square enclosure were isothermal, where as, the horizontal walls were assumed to be insulated. The partitions were also considered to be insulated. Nusselt number variations have been studied to determine the effect of Rayleigh number, partition height and partition position on natural convection in a differentially heated square cavity.

ANALYSIS

The physical model of the problem along with its boundary condition is shown in Figure 1. Considering the flow of fluid of constant properties as two-dimensional, steady, incompressible, the continuity equation and momentum equation in non-dimensional form are expressed using following non-dimensional variables,

$x^* = x/h,\ y^* = y/H,\ u^* = u/u_0,\ u_0 = \nu/H,$
$p^* = p/\rho u^2_0,\ T^* = (T_c)/T_h - T_c$

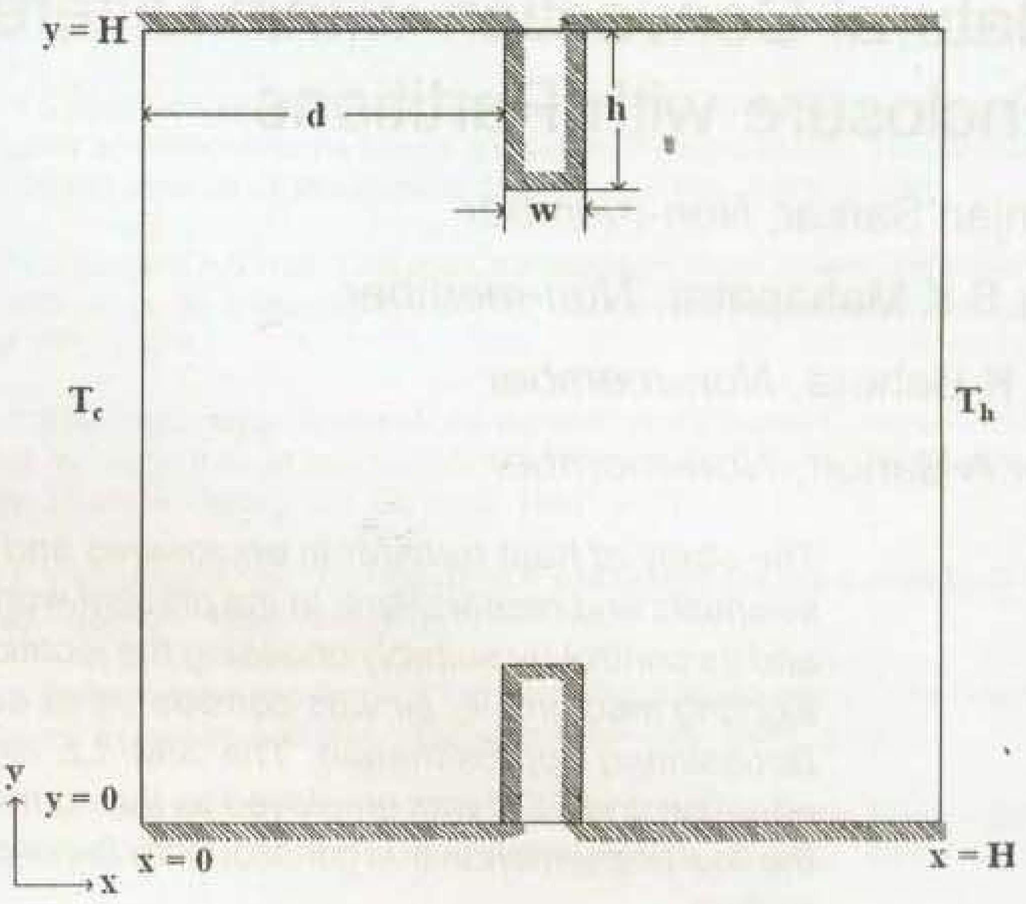

Figure 1 Computational test domain

as

continuity equation

$$\frac{\partial u^*}{\partial x^*} + \frac{\partial v^*}{\partial y^*} = 0 \tag{1}$$

The momentum equation

$$u^*\frac{\partial u^*}{\partial x^*} + v^*\frac{\partial u^*}{\partial y^*} = -\frac{\partial p}{\partial x^*} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 u^*}{\partial x^{*2}} + \frac{\partial^2 u^*}{\partial y^{*2}}\right) \tag{2}$$

$$u^*\frac{\partial v^*}{\partial x^*} + v^*\frac{\partial v^*}{\partial y^*} = -\frac{\partial p}{\partial y^*} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 v^*}{\partial x^{*2}} + \frac{\partial^2 v^*}{\partial y^{*2}}\right) + \frac{Ra}{\mathrm{Pr}}(T^*) \tag{3}$$

Energy equation can be expressed as,

$$u^*\frac{\partial T^*}{\partial x^*} + v^*\frac{\partial T^*}{\partial y^*} = \frac{1}{\mathrm{Re}\,\mathrm{Pr}}\left(\frac{\partial^2 T^*}{\partial x^{*2}} + \frac{\partial^2 T^*}{\partial y^{*2}}\right) \tag{4}$$

Above governing equations are subjected to following boundary conditions (as shown in Figure 1).

Boundary conditions

$$T^* = 0 \qquad x = 0,\quad 0 \le y \le 1$$

$$T^* = 1 \qquad x = 1,\quad 0 \le y \le 1$$

$$q_c = 0 \qquad y = 0, 1\quad 0 < x < 1$$

$q_c = -\partial T^*/n = 0$, for surfaces on partitions

$u^*, v^* = 0$ on all boundaries, where $q_c = -\partial T/n$ is the conductive heat flux on the wall.

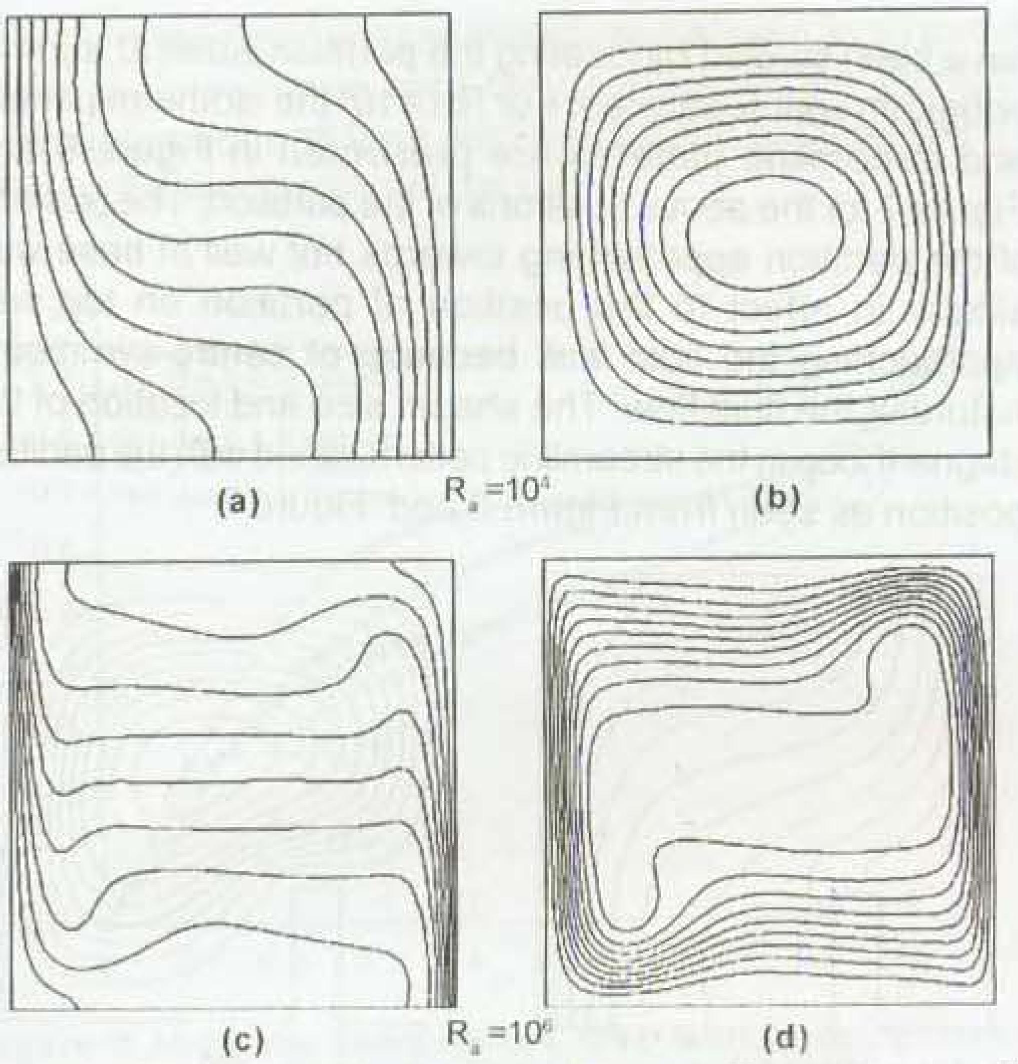

Figure 2 Variation of isotherm and streamline patterns with Rayleigh number for non-partitioned enclosure

NUMERICAL PROCEDURE

The governing equations outlined were discretized using finite element methods. Galerkin's weighted residual formulation had been employed for all governing equations. In the present work, a four noded iso-parametric rectangular element was used. The problem was analyzed using first order two-dimensional, four noded rectangular elements. 60 × 60 grid was used for all computation purpose after conducting grid independent test. The finite element based semi-implicit method for pressure linked equations called SIMPLE was adopted for obtaining the solution. Non-uniform meshing was adopted and finer meshing near the boundary is employed to capture the transport phenomenon. Relaxation parameter of 0.2 was chosen to obtain convergence for higher Rayleigh number. The convergence criteria, *ie*, difference between subsequent level of iterations, $\phi^{n+1} - \phi^{n} < 10^{-8}$ was fixed at 10^{-8}.

RESULTS AND DISCUSSIONS

From the governing equations already outlined, it was obvious that the phenomena was influenced by many parameters, such as, Ra, Pr and geometry of the partitions. Temperature of the active walls and Prandtl number were kept fixed during the present investigations.

The effect of Rayleigh number on the flow within differentially heated square cavity without partition were examined for two cases, *ie*, Ra = 10^4 and Ra = 10^6. Isotherm pattern and streamline pattern were presented for Ra = 10^4 and Ra = 10^6 in Figure 2.

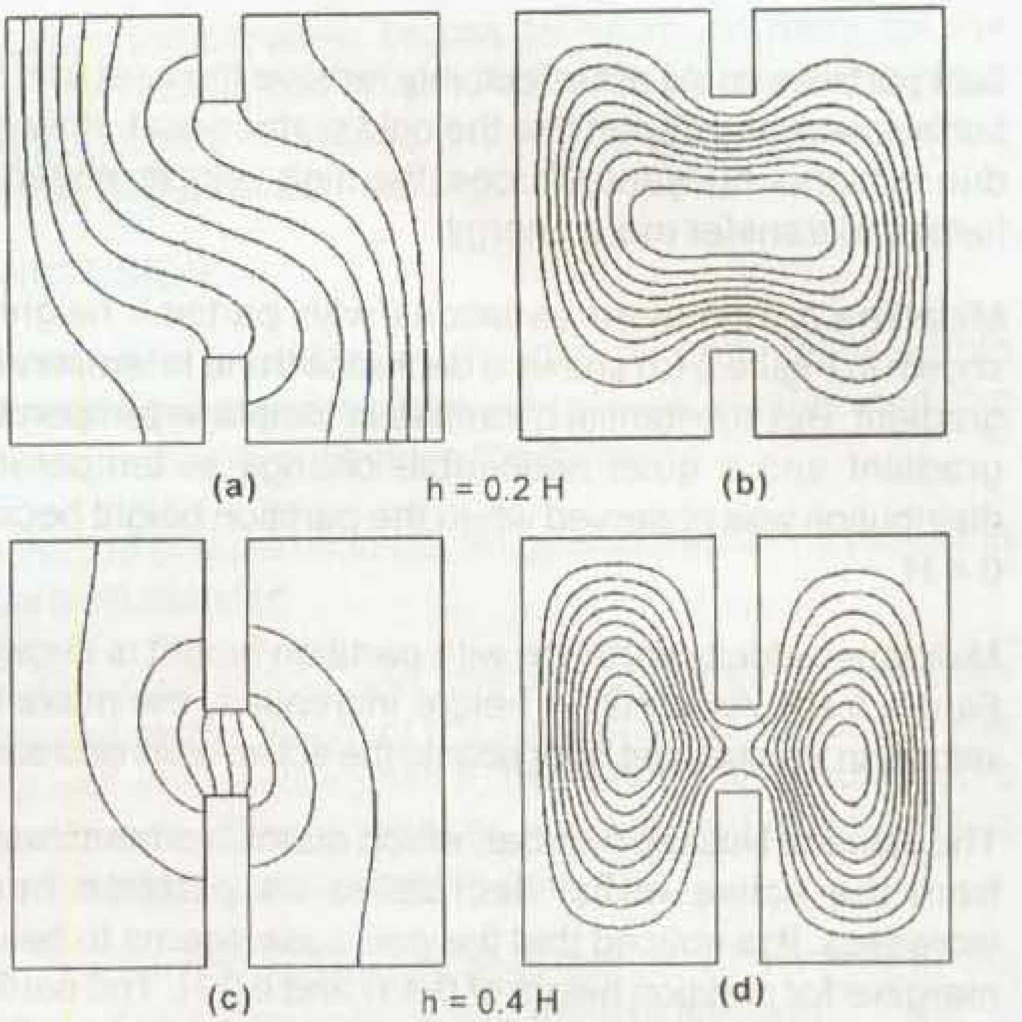

Figure 3 Variation of isotherm and streamline patterns with partition height for $R_a = 10^4$

Isotherms and streamlines for different partition height as shown in Figure 3 and Figure 4 depicted the flow phenomena for different Rayleigh numbers in the cavity. When the gap size between the top and bottom partition decreases with increase in partition height, crowding of isotherms has been observed in the gap. With increase in partition height, the low temperature region adjacent to cold wall increased as because the natural direction of flow was obstructed by the presence of partition. For Ra = 10^4 and Ra = 10^6 at a lower partition height, a better penetration of isotherms due to higher convective flow and the isotherms were more restricted to partition wall. Figure 3 and Figure 4 also reveals that when the partition height becomes 0.4 H, isolation of hot region from cold region is observed.

From the streamline pattern, it was observed that the shape and location of stagnant loop depended on the severity of shearing action induced due to partition. Two secondary cells existed for higher Ra as seen from Figure 4 indicating some

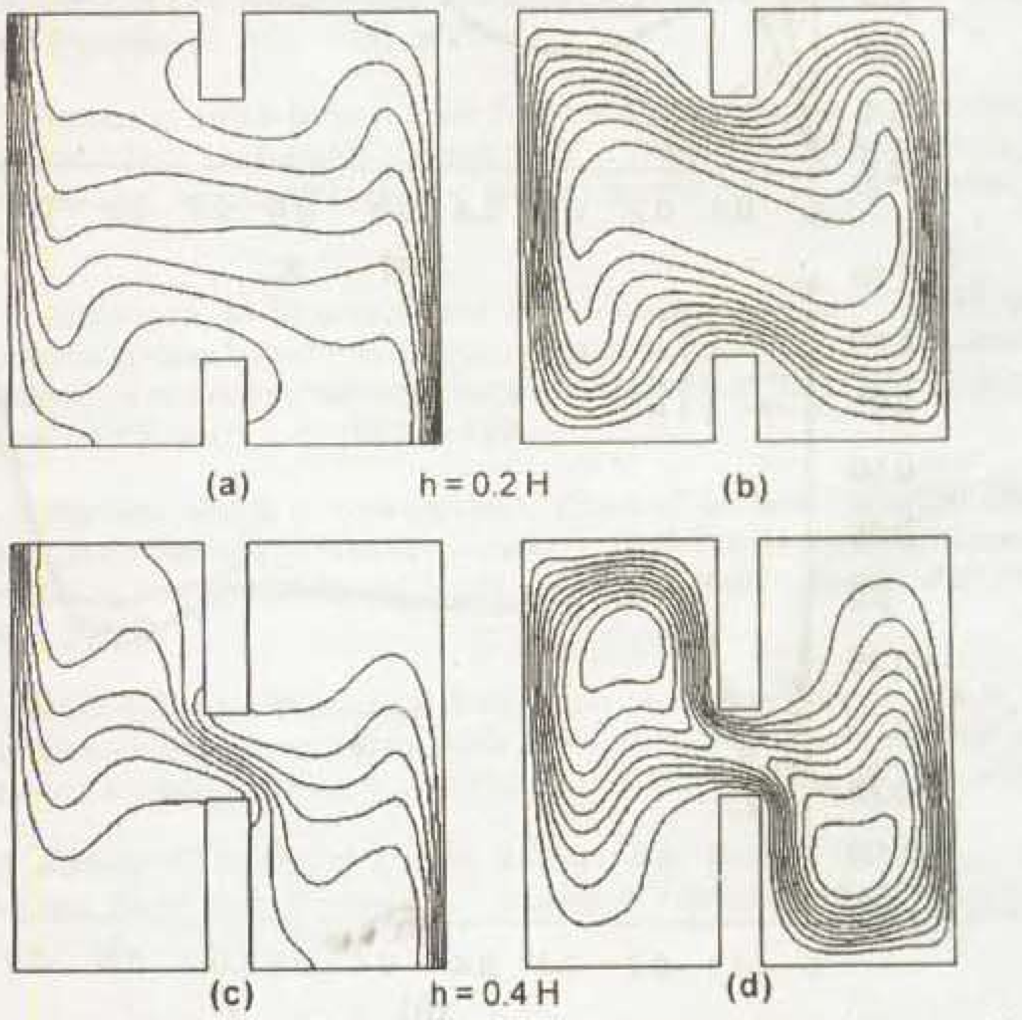

Figure 4 Variation of isotherm and streamline patterns with partition height for $R_a = 10^6$

fluid particles could not effectively remove the heat from hot surface wall and import it to the cold surface wall. However, due to higher buoyancy forces, the high velocity shear jets helped to transfer more energy.

Midplane temperature variations with partition height as shown in Figure 5 (a) shows a decrease trend in temperature gradient. But substantial decrease in midplane temperature gradient and a quiet noticeable change in temperature distribution was observed when the partition height became 0.4 H.

Midplane velocity variation with partition height is shown in Figure 5 (b). As partition height increases, the maximum velocity in the shear jet layer near to the active walls decreases.

The value of Nusselt number, which quantifies heat transfer from the active walls, decreases as partition height increases. It is noticed that the decrease seems to be very marginal for partition height of 0.1 H and 0.2 H. The partition height of 0.1 H is thought of as a soft resistance in addition to the inherent resistance offered by the boundary layer. The substantial decrease in Nusselt number however is seen for partition height of 0.4 H. This effect is somewhat more pronounced for higher value of Ra *ie*, 10^6.

In order to study the effect of position of partition, the height of the partition has been kept fixed at 0.3 H. Here two cases have been studied by locating the partition either at top wall or bottom wall separately. For Ra $=10^6$ the isotherm pattern and streamline patterns are presented in Figure 6 and Figure 7 for the above positions of the partition. The position of the partition approaching towards hot wall at base was similar in effect to the position of partition on top wall approaching the cold wall because of centro-symmetric nature of the fluid flow. The shape, size and location of the stagnant loop in the streamline pattern varied with the partition position as seen from Figure 6 and Figure 7.

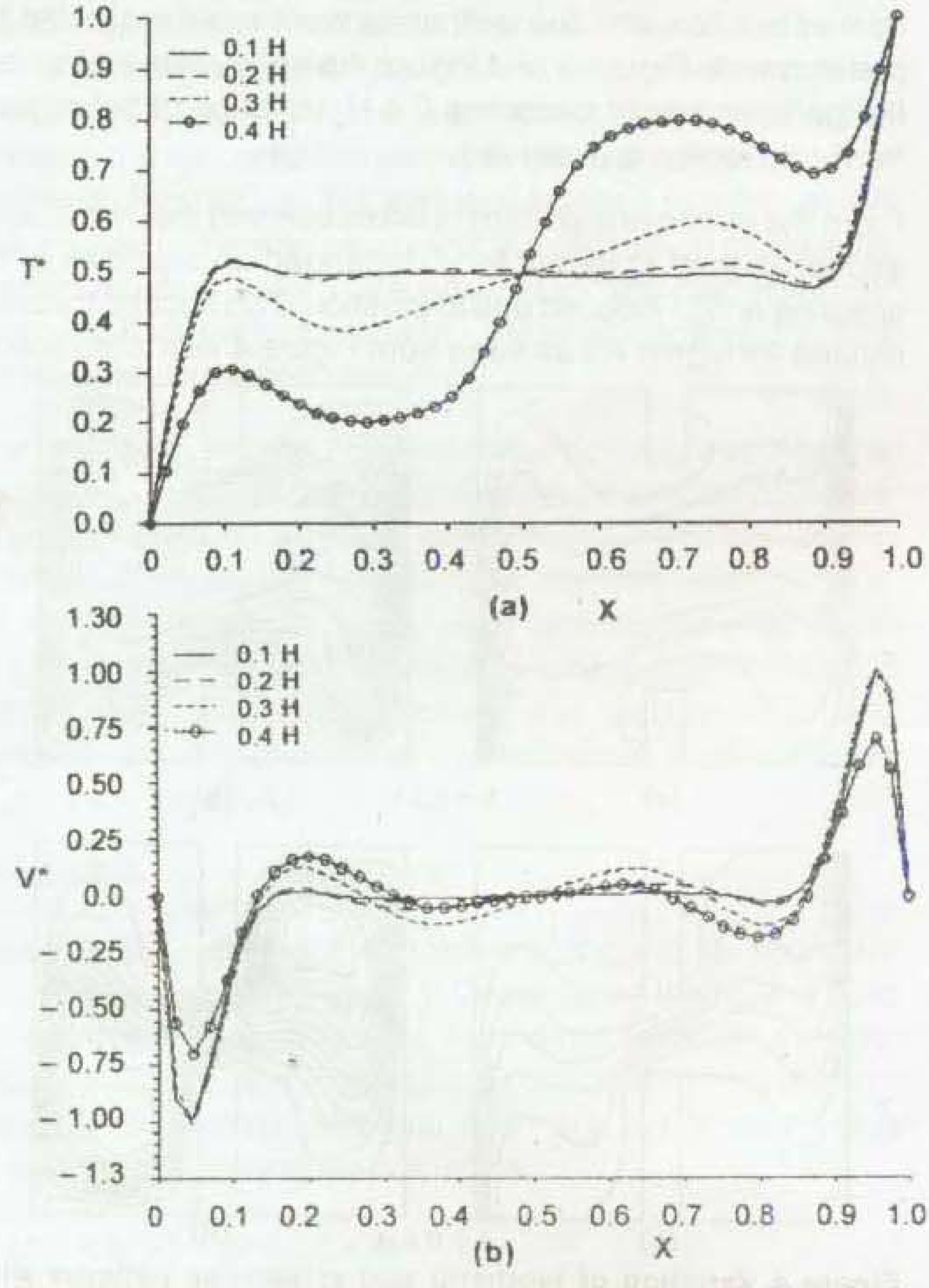

Figure 5 Midplane (a) temperature variation and (b) velocity variation with increasing partition height for $R_a=10^6$

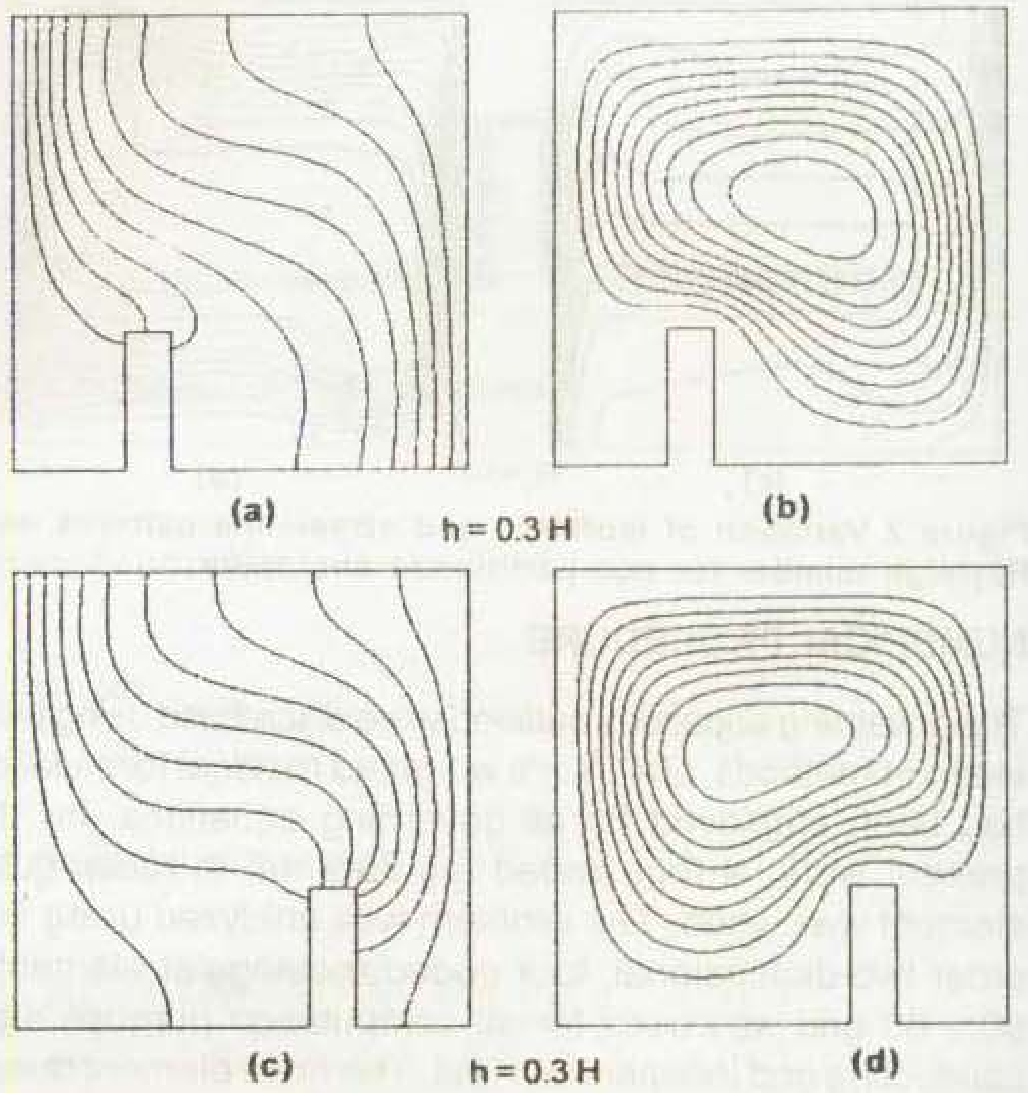

Figure 6 Isotherm and streamline patterns for partition position 0.3 H and 0.7 H from left wall for $R_a=10^4$

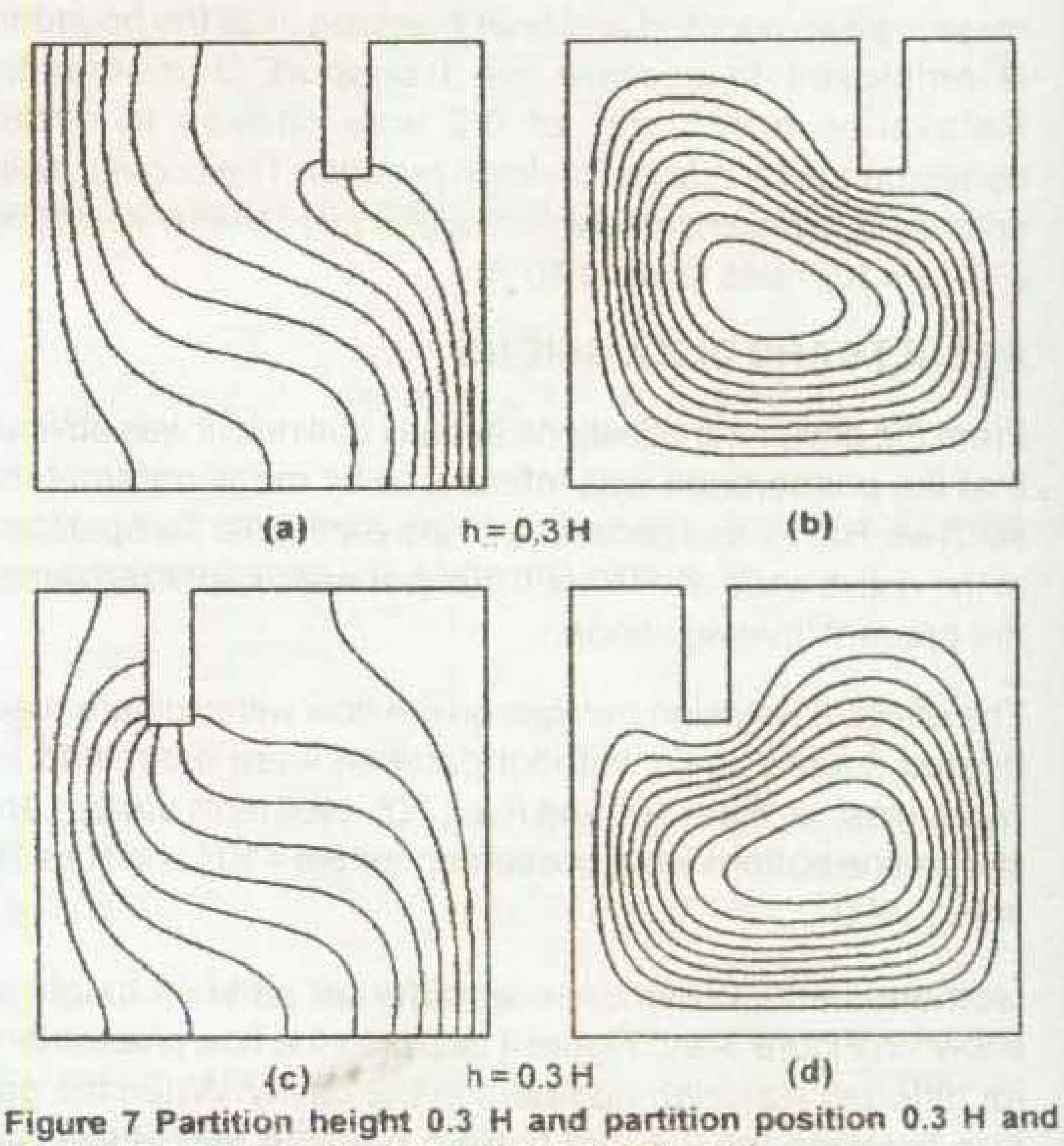

Figure 7 Partition height 0.3 H and partition position 0.3 H and 0.7 H from right wall, respectively for $R_a=10^4$

The midplane temperature distribution shown in Figure 8 shows a decrease in core temperature as the partition approaches hot wall from cold wall for the partition placed either at base or ceiling of the cavity.

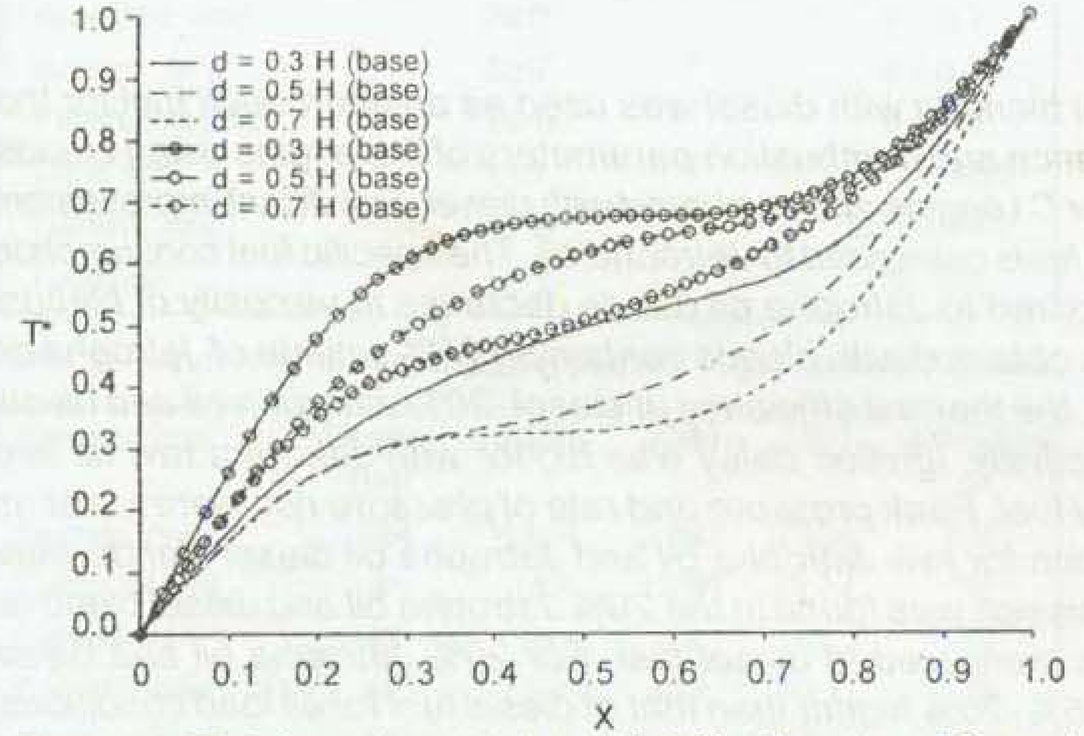

Figure 8 Midplane temperature distribution for different positions of partition at top and bottom wall, when $R_a = 10^4$ and h = 0.3 H

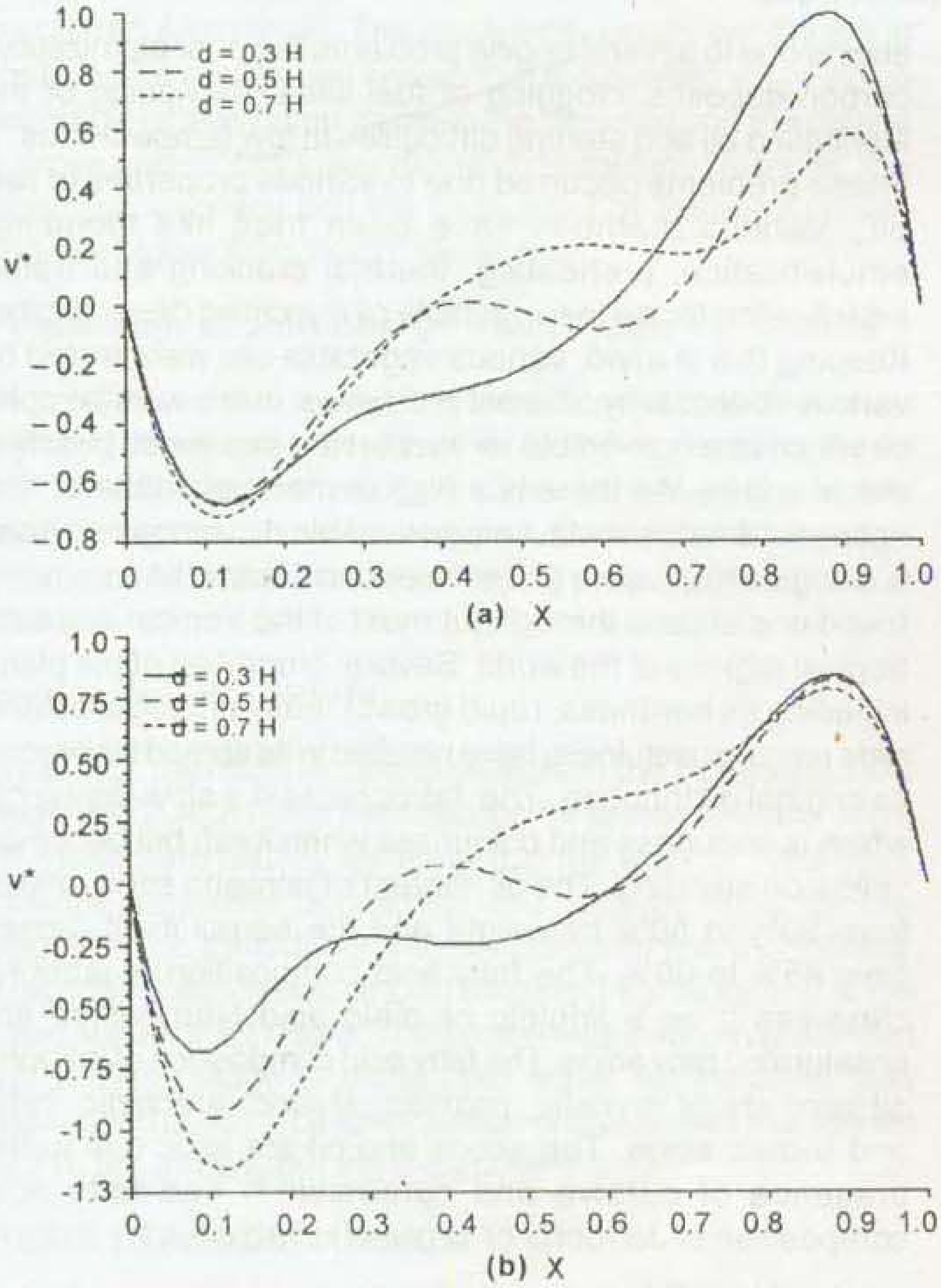

Figure 9 Midplane velocity variation for R_a=10⁴ with respect to partition position from left wall at base (a) and at ceiling; (b) when partition height is 0.3 H, where V_{max}(base) = 43.65×10^{-5}m/s, V_{max}(ceiling) = 31.73×10^{-5} m/s

The core temperature seems to be much more for the partition at ceiling and close to cold wall, compared to other configurations. The mid plane velocity was affected considerably as seen from Figure 9.

CONCLUSION

The effect of partition on the natural convection within differentially heated square cavity was studied and the conclusions were outlined in the following.

- As the mid partition height gets increased, it results in low heat transfer.
- The size, shape and position of the secondary cells depend on the height of the partition. The partition on the top wall when gets shifted towards hot wall, ensures more heat transfer. Similar features are observed as the partition on the base moves towards cold wall.
- The centro-symmetric flow feature of the fluid in the cavity is retained even in presence of partition.

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