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NUMERICAL SIMULATIONS OF NATURAL CONVECTION IN AN OPEN CAVITY WITH THE PRESENCE OF A SHROUDING WALL

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Abstract. *In this paper an investigation of natural convection in a square open cavity with the presence of a shrouding wall placed in front of the cavity opening forming a short vertical channel is conducted. The cavity vertical wall is isothermal and the horizontal walls are kept adiabatic. Laminar and two-dimensional flow is assumed for Rayleigh number ranging from* 10^3 *to* 10^7*. Two boundary conditions are considered for the shrouding wall, namely adiabatic and isothermal, and the distance between the shrouding wall and the cavity opening varies between 0.1 and 0.5 times the cavity height. The fluid properties are assumed constant except for the buoyancy term in which the Oberbeck-Boussinesq approximation is employed. The influence of Rayleigh number and the shrouding wall on the streamlines, isotherms, average Nusselt number and the velocity profiles at the top and bottom of channel are analyzed. The problem is numerically solved via the Finite Volume method. Given the difficulty in determining the boundary conditions at top (exit) and bottom (entrance) of the channel, extended domains are built in those regions.*

Keywords: *natural convection, open cavity, shrouding wall, extended domains.*

1. INTRODUCTION

Among the branches of thermal engineering, those regarding natural convection heat transfer inside cavities have been the subject of several studies during the last decades. The growing interest in this theme is related to the wide range of applicability in engineering problems, such as, building insulation, electronics cooling devices, drying process and solar cavity receivers. Due to the importance of the subject, several papers related to open cavities are found in the literature. Penot (1982) obtained numerical results of natural convection inside an isothermal open square cavity using the Oberbeck - Boussinesq approximation. The effects of Grashoff number and inclination of the cavity were analyzed. Chan and Tien (1985a) studied the open cavity with one vertical wall heated and the horizontal walls kept adiabatic. They included an extended computational domain once the velocity and the temperature boundary conditions could not be prescribed at the opening because at first they are unknown. They notice that the cavity exhibits a strong characteristic of its own and the near-field solutions in the interest region (inside the cavity and around the opening) become insensitive to the boundary conditions applied at the open borders

Franco and Ganzarolli (2006a) investigated the natural convection in a square open cavity with the presence of a shrouding wall forming a vertical open channel. They investigate the influence of the shrouding wall with two different boundary conditions, one adiabatic and the other isothermal. They conclude that when the shrouding wall is close to the cavity opening the flow pattern and the heat transfer process becomes strongly dependent of the boundary condition at the shrouding wall. However, when the shrouding wall is far from the opening, the cavity approaches the open cavity without the shrouding wall in spite of the boundary condition at this wall. Franco and Ganzarolli (2006b) presented a study of natural convection in a rectangular open cavity with the presence of an isothermal shrouding wall. They concluded that by controlling the geometric parameters and the Rayleigh number, it is possible to manage the heat transfer process by natural convection into the cavity, thus maximizing or minimizing de average Nusselt number, depending on the specific requirements of the engineering application.

Juarez *et. al.* (2011) studied the natural convection inside an open cavity considering temperature-dependent fluid properties. The effects of Rayleigh number and the temperature difference between the hot wall and the bulk fluid were analyzed.

The present paper investigates the natural convection heat transfer process in an open cavity with the presence of a shrouding wall. The shrouding wall is placed right in front of the cavity opening in order to form a short vertical channel. Once the boundary conditions at the inlet and outlet of this short channel are not known, an extended computational domain is applied in these regions. The effect of Rayleigh number, the shrouding wall boundary condition and the distance between the shrouding wall and the cavity opening are investigated.

2. PROBLEM FORMULATION

The open cavity and the shrouding wall are schematically shown in Fig.1. The two dimensional square cavity has a side-length L, with horizontal insulated walls and the left wall isothermally heated at T_h. The right side of the cavity is open to a short vertical channel formed by the presence of a shrouding wall of height $H = 3L$. A distance b separates the shrouding wall and the cavity opening. Two boundary conditions are considered for the shrouding wall, namely adiabatic and isothermal (at ambient temperature T_∞). The top and bottom of channel are open to a large and isothermal fluid reservoir maintained at T_∞. The numerical extent domains used at top and bottom of the channel to mitigate the uncertainty of the boundary conditions at the open surface are shown as dashed lines. Also, the vertical walls placed above and below the cavity opening are adiabatic.

The boundary conditions at the open borders are based on the boundary conditions imposed by Chan & Tien (1985).

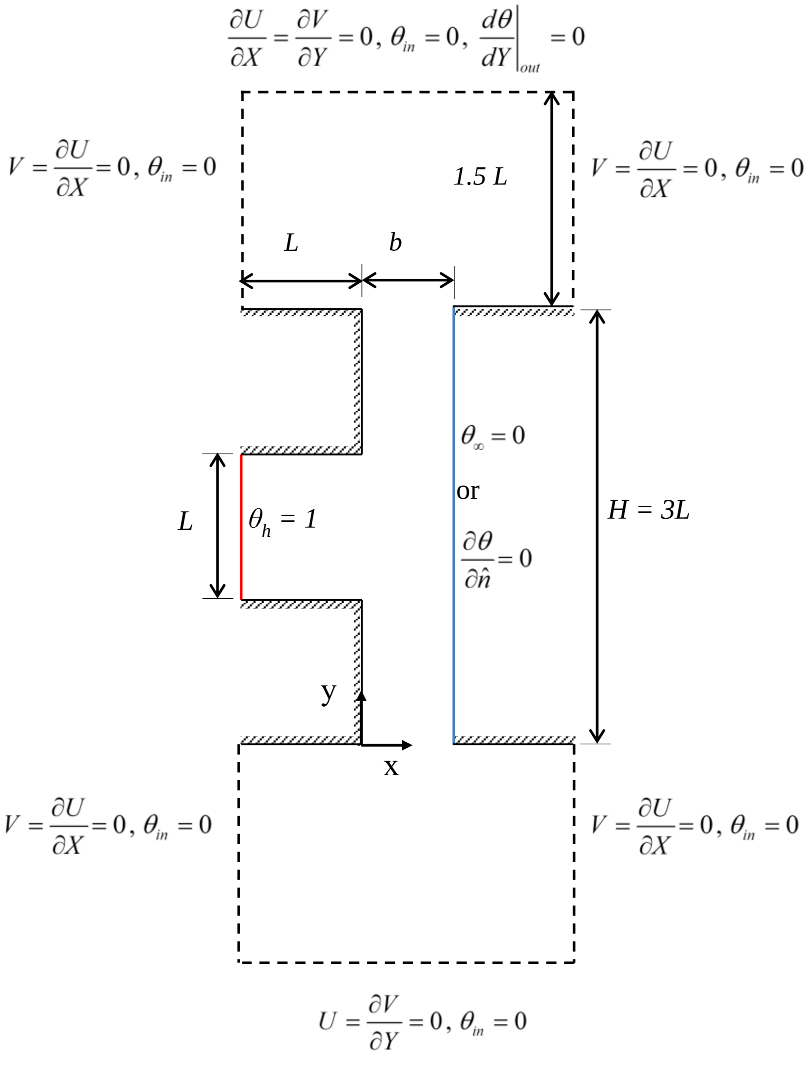


Figure 1. Geometry and boundary conditions

The flow is considered laminar and the fluid properties are constant. The Oberbeck-Boussinesq approximation for the governing equations is applied (fluid density variations neglected except in the buoyancy term) (Chan and Tien, 1985). The set of governing equations was written in dimensionless form using the group of nondimensionalized variables suggested by Chan and Tien, 1985:

$$\left(X,Y\right)=\frac{\left(x,y\right)}{L};\ \left(U,V\right)=\frac{\left(u,v\right)L}{\alpha};\ \tau=\frac{\alpha}{L^2}t;\ P=\frac{\left(p-p_\infty\right)L^2}{\rho\alpha^2};\ \theta=\frac{T-T_\infty}{T_h-T_\infty} \tag{2.1}$$

where α is the thermal diffusivity of fluid and ρ is the density of fluid.

The nondimensional balance equations for mass, momentum and energy become:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{2.2}$$

$$\frac{\partial U}{\partial \tau}+U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+Pr\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right) \tag{2.3}$$

$$\frac{\partial V}{\partial \tau}+U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+Pr\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+RaPr\theta \tag{2.4}$$

$$\frac{\partial \theta}{\partial \tau}+U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right) \tag{2.5}$$

where the quantities $Pr = \nu/\alpha$ and $Ra = g\beta(T_h - T_\infty)L^3/(\nu\alpha)$ are the Prandtl and the Rayleigh numbers, respectively.

The boundary conditions along the solid surfaces of the domain are the nonslip and impermeable conditions, i.e., $U=V=0$, and those imposed along the boundaries of the extended domains are include in Fig. 1. It is assumed that the incoming flow is at ambient temperature and for the outgoing flow the temperature gradient normal to the boundary is null.

Heat transfer across the open cavity is evaluated using the surface average Nusselt number along the heated wall, defined as

$$\overline{Nu}=\int_{hot\ wall}\left(\frac{\partial\theta}{\partial X}\right)dY=\overline{Nu}\left(Ra,\mathrm{Pr}\right) \tag{2.6}$$

The volumetric flow entering the bottom of the channel, $\dot{M}_{bottom}$ is determined by

$$\dot{M}_{bottom}=\int_{\substack{channel\\ bottom\,opening}} V_{in}\,dX \tag{2.7}$$

At the top of channel, the volumetric flow can either enter or exit the channel. The volumetric flow rate entering through the top of the channel, $\dot{M}_{top\_in}$ and the volumetric flow rate going out of the channel, $\dot{M}_{top\_out}$, are given by,

$$\dot{M}_{top\_in}=-\int_{\substack{channel\\ top\,opening}} V_{in}\,dX\quad;\quad \dot{M}_{top\_out}=\int_{\substack{channel\\ top\,opening}} V_{out}\,dX \tag{2.8}$$

The volumetric flow rate entering into the cavity through the opening, $\dot{m}$, are given by

$$\dot{m}=-\int_{\substack{cavity\\ opening}} U_{in}dY \tag{2.9}$$

The dimensionless stream function is defined as

$$\Psi\left(X,Y\right)=-\int_{X_0}^{X}V\left(X,Y\right)dX+\Psi(X_0,Y_0) \tag{2.10}$$

where the values of $\Psi\left(X_0,Y_0\right)$ are zero at the solid walls.

3. NUMERICAL PROCEDURE

The conservation equations are numerically solved using the finite volume method with the SIMPLEC algorithm (Van Doormaal and Raithby, 1984), QUICK scheme (Leonard, 1979) for interpolation of θ, U, V, and the PRESTO! method for P (Patankar, 1980).

A grid dependency test were performed for the most stringent case considered, Ra = 10^7, b = 0.5 and adiabatic boundary condition for the shrouding wall. Once the volumetric flow rates across the open boundaries showed to be more sensitive to mesh changes, those were the observed parameters during the grid dependency test. The results are shown in Tab. 1. The mesh size represents the number of control volumes inside the cavity.

Table 1. Effect of mesh size

Mesh size	$\dot{m}$	$PD(\dot{m})$	$\dot{M}_{bottom}$	$PD(\dot{M}_{bottom})$	$\dot{M}_{top\_in}$	$PD(\dot{M}_{top\_in})$	$\dot{M}_{top\_out}$	$PD(\dot{M}_{top\_out})$
50×50	94.26	3.16%	41.71	1.31%	60.24	2.85%	103.05	2.85%
100×100	91.28	0.57%	41.17	0.01%	58.53	0.49%	100.11	0.48%
150×150	90.77	0.23%	41.16	0.02%	58.24	0.10%	99.63	0.15%
200×200	90.56	-	41.15	-	58.18	-	99.48	-

The percentage deviation is defined as:

$$PD_k = \frac{\left|\phi_k - \phi_{k+1}\right|}{\phi_k} \times 100 \tag{3.1}$$

It may be noticed that when the number of control volumes inside the cavity is increased from 150×150 to 200×200 all the percent deviations are less than 0.5%. In this way, a uniform grid with 150×150 control volumes inside the cavity was adopted in the present work for all cases.

4. RESULTS AND DISCUSSION

Numerical results were obtained for the Rayleigh number ranging from 10^3 to 10^7. The value of the ratio $B = b\,/\,\mathrm{L}$ were 0.1, 0.2 and 0.5 and the Prandtl number was fixed at 1.0. For the shrouding wall, two different boundary conditions were considered, the wall adiabatic and the wall isothermal kept at ambient temperature. A summary of the parameters investigated is presented in Tab. 2**.**

Table 2. Summary of parameter values used in the present study

Ra	10^3, 10^4, 10^5, 10^6, 10^7
Pr	1
B	0.1, 0.2, 0.5

Figure 2 exhibits streamlines and isotherms adiabatic boundary condition for the shrouding wall and the solid lines represent the results with the isothermal shrouding wall. The flow and the heat transfer process inside the cavity are heavily influenced by the boundary conditions of the shrouding wall when B = 0.1. For the isothermal boundary condition, the circulation inside the cavity approaches the circulation in a closed cavity with the sidewalls at different temperatures (Franco and Ganzarolli, 2006a). For the adiabatic boundary condition, the fluid flows more easily through the channel because the adiabatic wall warms a larger portion of the fluid facilitating its displacement. When B increases to 0.5, the pattern of the streamlines and isotherms are practically the same for the both boundary conditions of the shrouding wall obtained with Ra = 10^5 and the ratio B = 0.1, 0.2 and 0.5. The dashed lines represent the results considering the adiabatic boundary condition for the shrouding wall and the solid lines represent the results with the isothermal shrouding wall.

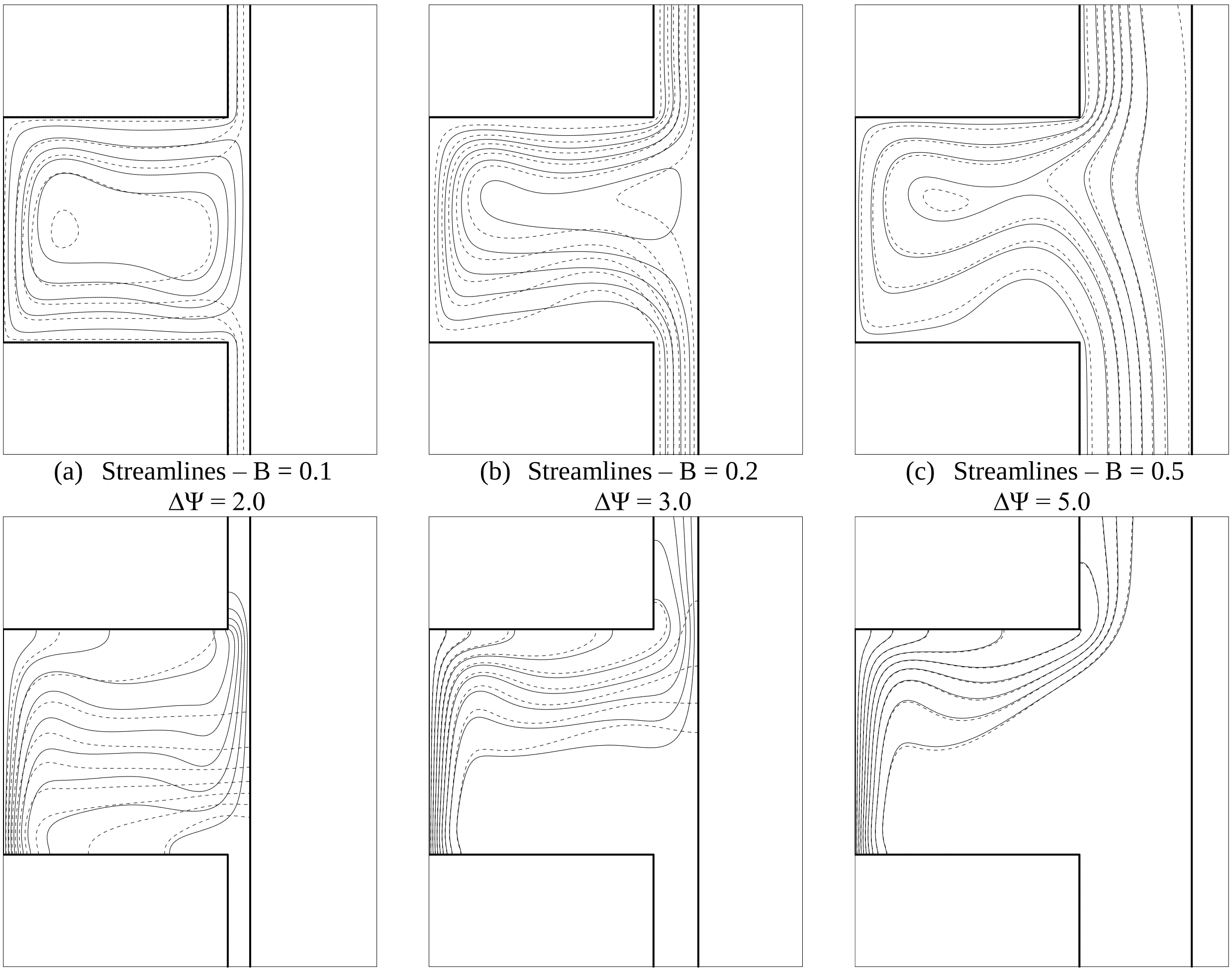
Figure 3a shows the influence of the Ra and the ratio B on the volumetric flow rate entering the cavity $\dot{m}$. As the Ra number increases the value of also increases. The $\dot{m}$ also increases when B varies from 0.1 to 0.2, regardless of the Ra. However, when B changes from 0.2 to 0.5 the flow rate $\dot{m}$ diminishes for higher Ra values (Ra = 10^6 and 10^7).

The influence of the boundary condition on $\dot{m}$ is shown in Fig.3b. The is a parameter used to compare the results obtained for the $\dot{m}$ with the two different boundary conditions.

$$\Delta\dot{m} = \frac{\left(\dot{m}_{iso} - \dot{m}_{adi}\right)}{\dot{m}_{iso}} \times 100 \tag{4.1}$$

where $\dot{m}_{iso}$ represents the results obtained for $\dot{m}$ with the isothermal boundary condition at the shrouding wall and $\dot{m}_{adi}$ the results for the adiabatic shrouding wall.

For wide channels (B = 0.5), once the value of $\dot{m}_{iso}$ and $\dot{m}_{adi}$ are similar, $\Delta\dot{m}$ results in almost zero with Ra ranging from 10^4 to10^7, indicating that the flow is not extensively affected by the boundary condition of the shrouding wall. When the value of *B* becomes smaller, there is an increased influence of the boundary condition with the increase of Ra. For *B* = 0.2, once $\Delta\dot{m}$ results in negative values, the flow rate $\dot{m}$ is greater when the adiabatic boundary condition is considered. For B = 0.1 the isothermal shrouding wall favors the entering the cavity when Ra is smaller than 10^6. For Ra = 10^7 the value of $\dot{m}$ becomes higher when the shrouding wall is considered adiabatic compared with the isothermal wall.

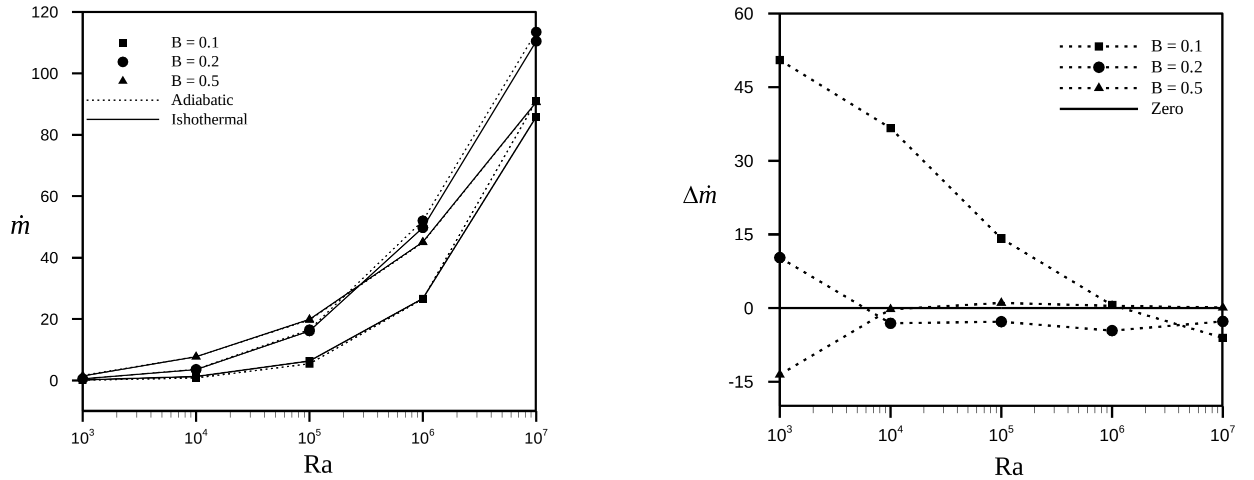


(a) Streamlines – B = 0.1 $\Delta\Psi = 2.0$
(b) Streamlines – B = 0.2 $\Delta\Psi = 3.0$
(c) Streamlines – B = 0.5 $\Delta\Psi = 5.0$
(d) Isotherms – B = 0.1 $\Delta\theta = 0.1$
(e) Isotherms – B = 0.2 $\Delta\theta = 0.1$
(f) Isotherms – B = 0.5 $\Delta\theta = 0.1$

Figure 2. Streamlines and isotherms obtained for *Ra* = 10^5

The volumetric flow rate entering through the bottom and the top channel opening are shown in Fig. 4a and Fig 4b, respectively. Similarly the volumetric flow rate entering the cavity, $\dot{m}$, the flow rate entering the channel from the bottom, $\dot{M}_{bottom}$, increases with increasing *Ra* number. Also, the volumetric flow rate $\dot{M}_{bottom}$ increases when *B* varies from 0.1 to 0.2, regardless of the *Ra*. However, when *B* changes from 0.2 to 0.5 the flow rate $\dot{M}_{bottom}$ also diminishes for higher *Ra* values (*Ra* = 10^6 and 10^7). The reduction of $\dot{M}_{bottom}$ coincides with the increases of the volumetric flow entering the top of the channel, $\dot{M}_{top\_in}$. The buoyancy forces, responsible for the movement of fluid in the natural convection, can be so strong that for high Ra values, the flow is induced from the cavity opening toward the top of the channel. According to

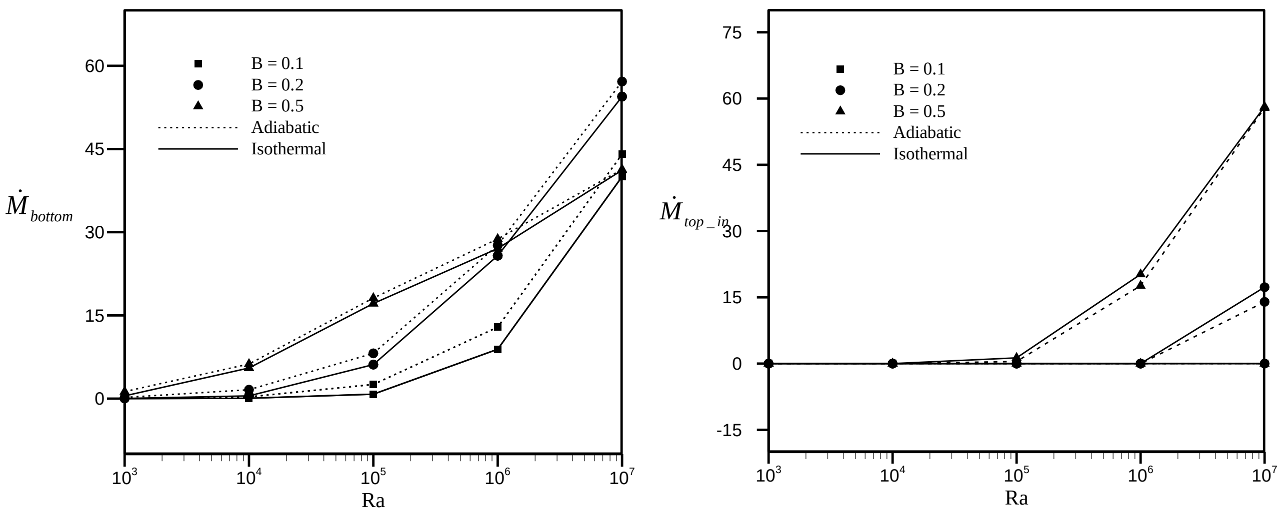
Fig. 4b, this phenomenon can be observed for B = 0.2 for Ra number 10^7, once $\dot{M}_{top\_in} > 0$, and for B = 0.5 for Ra number starting from 10^5.



(a) (b)

Figure 3. (a) Effect of the *Ra* and the ratio *B* on the volumetric flow rate entering the cavity. (b) Effect of the boundary condition on the flow rate entering the cavity.

The average Nusselt number as a function of the Rayleigh number is showed in Fig. 5. For Ra = 10^7 the Nusselt number is not affect by the ratio B neither by the shrouding wall boundary condition. Decreasing the Ra number the ratio B starts to affect more significantly the Nusselt number. For Ra = 10^6 and 10^5, when B varies from 0.2 to 0.1 the value of Nu decreases and for Ra = 10^4 the decrease in Nusselt value is perceived even when B changes from 0.5 to 0.2. The wall boundary condition does not affect the results for Nusselt when B = 0.5 because the shrouding wall is far enough. For B = 0.2, only when Ra = 10^3 a difference between the results for the two boundary conditions is perceived. For B = 0.1, the heat transfer in the hot wall is considerably affected by the boundary condition when the Rayleigh number is less than 10^5. The adiabatic boundary condition decreases the Nusselt number compared with the isothermal boundary condition in all the cases showed in Fig. 5.



(a) (b)

Figure 4. Volumetric flow rate entering through the (a) bottom and the (b) top channel open boundary.

5. CONCLUDING REMARKS

A numerical study of natural convection in a square open cavity has been conducted. The influence of a shrouding wall placed in front of the cavity opening, forming a short vertical channel, was analysed for two different boundary conditions of the shrouding wall:, adiabatic or at constant temperature. The effects of Rayleigh number was observed and it was observed that the greater the value of Ra less significant is the influence of the shrouding wall on the results presented for the average Nusselt number and the volumetric flow rate measured at the cavity opening and at the top and bottom channel opening. As the ratio B decreases, the heat transfer process inside the cavity becomes stronger dependent of the boundary condition at the shrouding wall. The isothermal boundary condition favours the heat transfer process compared to the adiabatic boundary condition.

For high values of Ra and B flow is induced through the channel top opening. This causes a drop in the volumetric flow rate measured at the channel bottom opening and at the volumetric flow rate induced into the cavity. However, the Nusselt number is not affect by this phenomenon.

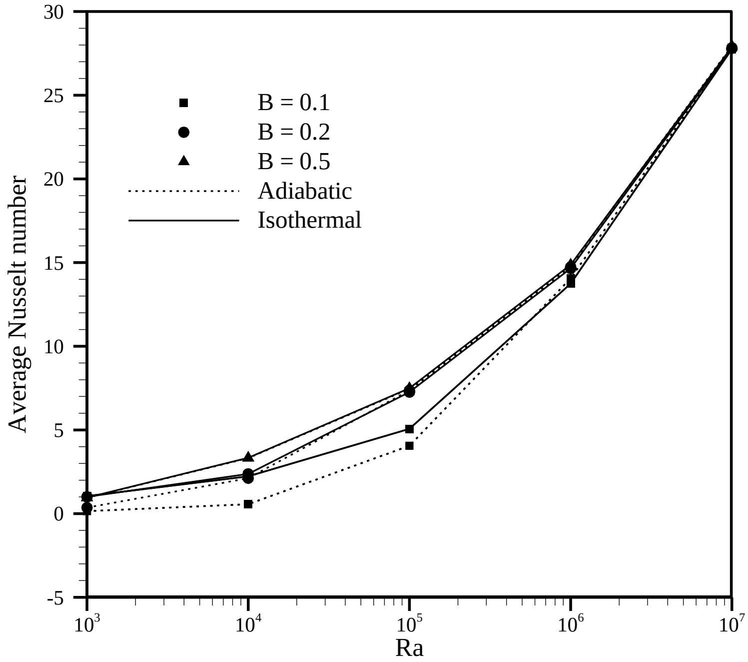


Figure 5. Average Nusselt number as a function of Ra.

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