Effect of the Size and Position of Two Heat-generating Blocks on Natural Convection inside a Closed Cavity

R. Hidki[a], L. El Moutaouakil, Z. Charqui[b], M. Boukendil[c] and Z. Zrikem[d]
LMFE, Department of Physics, Cadi Ayyad University, Faculty of Sciences Semlalia, Marrakesh, Morocco

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Abstract: This work aims to numerically study natural convection in a square cavity with two heat-generating blocks. The cavity is cooled uniformly via its right vertical wall, while the remaining walls are thermally insulated. The Finite Volume Method (FVM) with the SIMPLE algorithm is employed for discretization and solving the differential equations. The results are presented to clarify the effect of the size and position of the two blocks for $Ra_m = 10^6$, $Pr = 0.71$, and $K = 0.1$. These results are reported in terms of streamlines and isotherms. According to our findings, the size and position of two generating blocks significantly influence the cavity's fluid flow and heat transfer.

1 INTRODUCTION

Because of its practical importance, natural convection in a closed cavity contains heating blocks (active or inactive) has attracted the attention of several scientific researchers (Pandey et al., 2019). This cavity model can be applied in many engineering fields, namely cooling of electronic devices, solar collectors, cooling, and heating of buildings. Many researchers have focused on this problem (Nardini et al., 2016, Paroncini and Corvaro, 2019, and Hidki et al., 2021), either from the numerical accuracy point of view of the calculation or the point of view to improve the thermal behavior.

In the literature, the authors considered the case of one or several isothermal blocks (Dash and Lee, 2014, Pordanjani et al., 2018, and Sheikholeslami and Vajravelu, 2018), the case of a conductive block (House et al., 1990 and Lima and Ganzarolli, 2016), and the case of a heat-generating block (Sivaraj et al., 2020). In the last case, which is the most practical, few studies were found. Among them, the contributions of (Oh et al., 1997 and Ha et al., 1999), who numerically studied the effect of a heat-generating square block on natural convection in a differentially heated cavity. The authors analyzed the impact of the internal temperature difference (ΔT) and the Rayleigh number on the flow and heat transfer in the cavity. Later on, the same problem was studied by (Lee and Ha, 2006) in a cavity heated from below and cooled from above. The authors analyzed the effect of the internal and external Rayleigh numbers, the thermal conductivity ratio on the dynamic and thermal characteristics in the cavity. Their results show that if $\Delta T = 25$, the isotherms are insensitive to the variation of the thermal conductivity ratio.

This literature review shows that natural convection in closed cavities with heat-generating blocks is up-to-date research due to its practical application in engineering, such as cooling of electronic components, heat exchangers, buildings, etc. Therefore, according to these findings and our knowledge, the case of two square heat-generating blocks of different sizes and positions in a closed cavity cooled by one of its sides has not been treated. However, the main objective of the present work is to study the effect of the size and position of two heat-generating blocks on the dynamic and thermal characteristics of the flow in a square closed cavity.

[a] https://orcid.org/0000-0002-6727-3092
[b] https://orcid.org/0000-0002-2987-3046
[c] https://orcid.org/0000-0001-7058-2120
[d] https://orcid.org/0000-0002-1786-4310

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2 MATHEMATICAL FORMULATION

The physical problem considered is schematized in Figure 1. It is an air-filled square-shaped cavity, with the right vertical wall cooled with a constant temperature T_c. The remaining walls are thermally insulated. Two square heat-generating blocks with different sizes $S_{1,2} = w_{1,2}/L$ are placed inside the cavity. The blocks generate the same amount of energy ($Q_1(W/m^3) = Q_1(W/m^3) = Q_m(W/m^3)$). The latter are placed at three different heights ($Y_1 = 0.25$, $Y_2 = 0.5$, and $Y_3 = 0.75$) and fixed in the X-direction (block 1 at $X_1 = 0.25$ and block 2 at $X_2 = 0.75$). All thermophysical properties of air are independent of temperature, except for the density in the buoyancy term for which the Boussinesq approximation is adopted. The thermal radiation is negligible.

By introducing these approximations in the continuity, Navies-Stokes, and energy equations, we obtain the following system of non-dimensional equations:

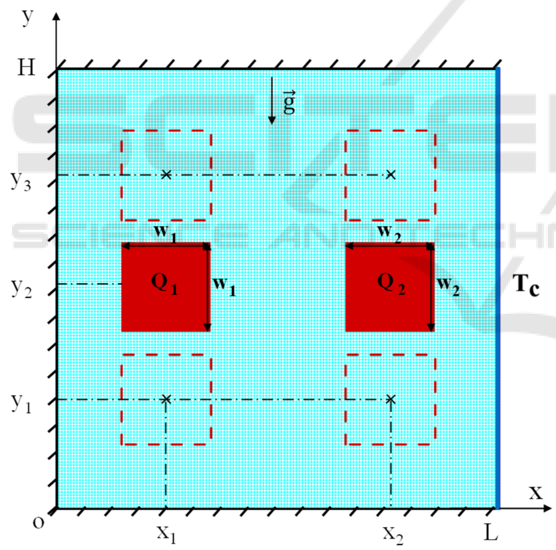

Figure 1: Studied configuration.

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \quad (1)$$

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

$$\frac{\partial V}{\partial \tau}+U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\Pr\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+\Pr Ra_m\theta \quad (3)$$

$$\frac{\partial \theta}{\partial \tau}+U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right) \quad (4)$$

$$\frac{\partial \theta}{\partial \tau}=K\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right)+\frac{Ra_i}{Ra_m} \quad (5)$$

The non-dimensional parameters, i.e., Rayleigh number, Prandtl number, and thermal conductivity ratio involved in these equations, are given by:

$$Ra_m=\frac{g\beta L^5 Q_m}{\nu\alpha_f k_f};\ \Pr=\frac{\nu}{\alpha_f};\ K=\frac{k_s}{k_f}$$

The non-dimensional boundaries conditions are specified as follows:

- On all solid walls: $U = V = 0$
- On the right vertical wall: $\theta(1, Y) = 0$
- On the bottom, left, and top walls:
  $\frac{\partial \theta}{\partial X}(0, Y)=\frac{\partial \theta}{\partial Y}(X, 0 \text{ or } 1)=0$
- On the solid-fluid interfaces of the blocks:
  $\frac{\partial \theta_f}{\partial n}=K\frac{\partial \theta_s}{\partial n}$ where n is the normal direction to the block surfaces.

3 NUMERICAL APPROACH AND VALIDATION

The above governing equations (1)-(5) and different boundary conditions are solved by using the SIMPLE (Semi Implicit Method for Pressure Linked Equations) algorithm based on the finite volume method. The uniform grid was used in the x and y directions.

The numerical code has been validated with the experimental and numerical data of (Paroncini and Corvaro, 2009). They studied natural convection in the presence of a hot rectangular block inside a square cavity cooled by its vertical walls. Comparative results in terms of the mean Nusselt number, at the upper surface of the hot block, are shown in Table 1. The obtained results show good agreement with the numerical simulation and also with experimental results.

Table 1: Mean Nusselt number for different values of Rayleigh number.

	Mean Nusselt number		
	Paroncini and Corvaro, 2009		
$Ra \times 10^5$	Num	Exp	Present work
1.24	3.67	3.58	3.71
1.46	3.74	3.62	3.79
1.76	3.82	3.78	3.89
2.05	3.89	3.85	3.98
2.25	3.93	3.93	4.03

4 RESULTS AND DISCUSSION

4.1 Effect of Block Size

To investigate the effect of the block size, Figures 2 and 3 give, respectively, the streamlines and isotherms for different values of S_1 and S_2 with $Ra_m = 10^6$, $Pr = 0.71$, and $K = 0.1$.

For $S_1 = S_2 = 0.1$ (Figure 2a), the streamlines show that the flow structure is almost symmetrical concerning the horizontal median of the cavity even though the Rayleigh number is important ($Ra_m = 10^6$). This can be explained by the fact that the blocks have a small size and therefore do not produce enough energy to circulate the air quickly in the cavity. This structure consists of a large clockwise cell encircling block 1 and descending into the space limited by the cold wall and block 2. Two low-intensity cells appear just below and above block 2 (closest to the cold wall), contributing to its cooling. For $S_2 = 0.4$ (Figure 2a), the flow comprises two primary cells in opposite directions. One clockwise cell encircles block 2, and another counterclockwise cell surrounds block 1. The first cell is three times more intense than the second and occupies a large part of the cavity. The secondary cells appearing around block 2 in the previous case are still present, but this time with large sizes. It should be noted that the flow symmetry observed in the case $S_1 = S_2 = 0.1$ is broken after increasing S_2. On the other hand, Figure 2a also shows that the maximum streamline function (Ψ_{max}) is not very sensitive to the variation of S_2. Indeed, when S_2 varies from 0.1 to 0.4, Ψ_{max} goes from 2.28 to 2.03, i.e., a relative difference that does not exceed 11%. In the case where $S_1 = 0.4$ and $S_2 = 0.1$ (Figure 2b), the flow is more intense around block 2, and it is almost stagnant between block 1 and the vertical passive wall. It should also be noted that the flow intensity is very sensitive to the variation of S_2. Indeed, Ψ_{max} changes from 4.75 to 3.19 when S_2 passes from 0.1 to 0.4, i.e., a relative difference of 33%. Since when the size of the blocks is large, the fluid does not have enough space to flow freely in the cavity. In addition, the viscous friction forces are high because they are proportional to the size of the blocks.

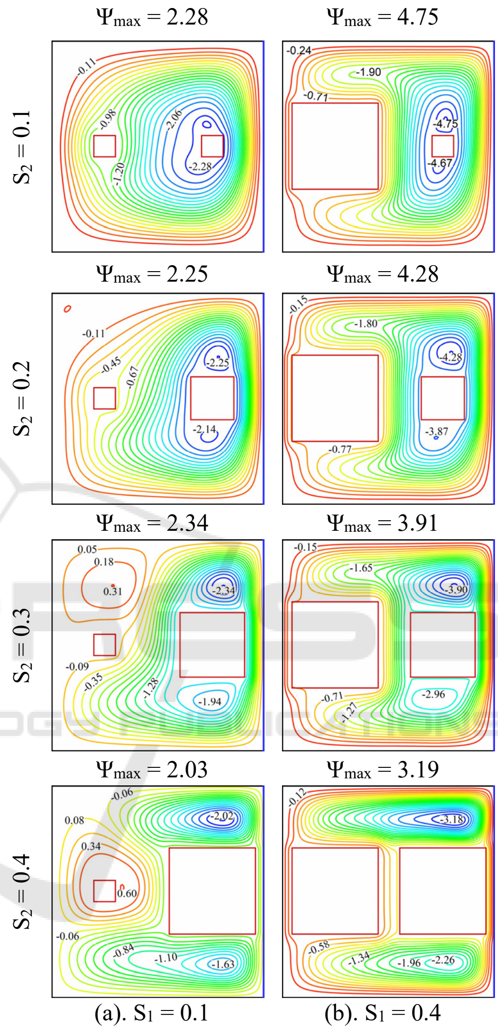

Figure 2: Streamlines obtained for different combinations (S_1, S_2).

The isotherms, Figure 3 shows that, in general, these lines are concentrated in the largest block and tight in the fluid medium. The isotherms are almost parallel to the cold wall for $S_1 = S_2 = 0.1$ (Figure 3a). This means that the local heat transfer is uniform on it. It can be noted that when we increase S_2 while keeping S_1 fixed at a given value, the maximum temperature rises rapidly. This is because of the domination of conductive heat exchange over convective one. Consequently, the fluid is unable to evacuate the heat generated by two blocks. For $S_1 =$ 0.4, the maximum temperature is insensitive to the variation of S_2 ($0.1 \leq S_2 \leq 0.3$). It should be noted that the temperature of block 2 is the lowest for all values of $S_2 \leq S_1$.

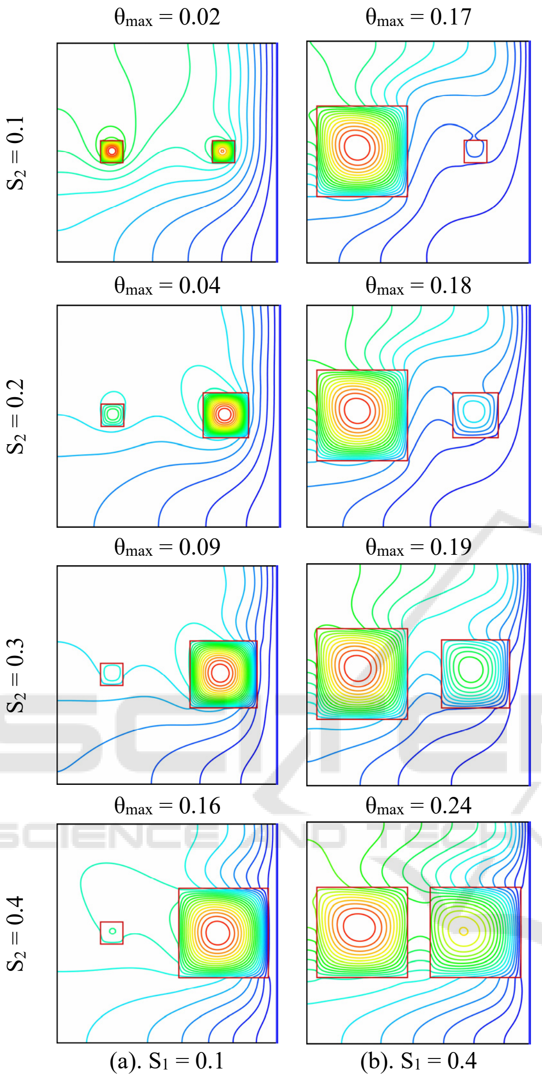

Figure 3: Isotherms obtained for different combinations (S_1, S_2).

4.2 Effect of the Position of the Blocks

In this section, the effect of the blocks' position on streamlines and isotherms is studied for $S_1 = S_2 = 0.3$ and $Ra_m = 10^6$.

In Figure 4, the streamlines and isotherms are plotted for three different positions of the blocks (P_1: bottom position, P_2: center position, P_3: top position). The streamlines (Figure 4a) show that the position of the blocks significantly affects the structure and intensity of the flow in the cavity. Indeed, when the blocks are placed at position P_1, the flow structure consists of two primary cells; the first one encircles the two blocks, and the second one develops above the two blocks. The latter has a vital role in the simultaneous cooling of the blocks. When moving from P_1 to P_2, the flow changes from bicellular to multicellular, and the flow intensity reduces by 47% (Ψ_{max} goes from 6.53 to 3.46). On the other hand, switching from position P_2 to P_3, Ψ_{max} remains practically unchanged (2.3% difference). The structure of the flow changes from multicellular to the initial state (i.e., bicellular).

The isotherms in Figure 4b show that these lines are always concentrated in the heat-generating blocks for the three positions analyzed. It can be noted, when comparing the three positions, that the lowest maximum temperature of the blocks is indicated in the two positions P_1 and P_2, and the highest temperature is noted in position P_3. From these findings (Figure 4), it can be concluded that positions P_1 and P_2 are the best for the excellent cooling of both heat-generating blocks.

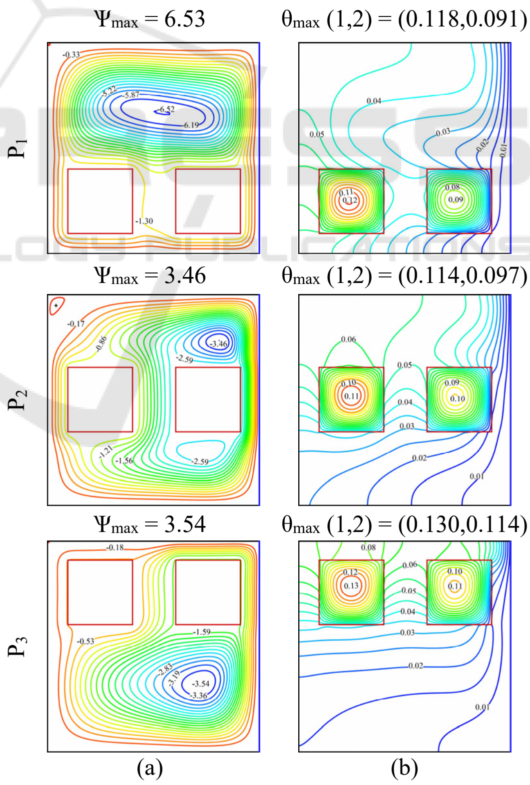

Figure 4: Streamlines (a) and isotherms (b) for $S_1 = S_2 = 0.3$ and different positions of the blocks.

5 CONCLUSION

In this work, the effect of the size and position of two heat-generating blocks inside a closed air-filled cavity on the streamlines and isotherms is numerically analyzed for $Ra_m = 10^6$ using FVM. The main results that can be drawn from this study are as follows:

- The size and position of the two blocks significantly affect the flow and temperature field inside the cavity.
- The isotherms are more concentrated in the largest block.
- The maximum temperature increases rapidly with S_1 and S_2.
- The position P_1 or P_2 should be chosen for the excellent cooling of the two studied blocks.

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