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Numerical Simulation of Heating and Ventilation by Natural Convection in a Square Cavity

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Abstract

Heating and ventilation in the building is essential to establish thermal comfort. The modern means invented to provide us with our heating and ventilation needs are generally expensive and represent sources of pollution. It is for this reason that there are several studies directed towards the research of renewable energies and non-polluting economic systems. The simulation of such a natural system at an almost low cost is the subject of our study in this work. In this work, a numerical study of passive heating and ventilation was made by natural convection in a room containing a heated vertical wall. In the case of heating, the system is closed and two openings are considered in the heated vertical wall allowing the re-circulation of the air in the room and therefore the heating of this latter. In the case of ventilation, the room is open to the outside through two inlet and outlet openings allowing the air circulation from the outside into the room and from the room into the outside which leads to ventilate the room. Numerical results with different mesh and Rayleigh number have been presented and their effects have been discussed.

Keywords: natural convection, passive heating, passive ventilation, TROMBE Wall, solar chimney NAVIER-STOKS, BOUSSINESQ

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1. Introduction

Thermal comfort in buildings is a very important topic in human life. It is the subject of a lot of research. Currently, one can ensure this comfort via several technological means, which can be expensive. Particular attention is paid to the orientation towards simple, economical and non-polluting techniques with relatively high efficiency. In this context passive heating and ventilation (by natural convection) are of great importance in the energy and economic sides of buildings. In natural convection, the movement of the fluid occurs by natural means such as buoyancy. Since the velocity of the fluid associated with natural convection is relatively low, the heat transfer coefficient encountered in natural convection is also low.

Many researches has been found in the field of heating by natural convection. Trombe Wall devices have been the subject of numerous studies in temperate climate and have proven their effectiveness as a passive heating system (Boyer et al [1]). Sarris et al [2] did a study to better understand some notions about natural convection in rectangular tanks locally bottom-heated. Hami et al [3] studied the modeling of natural convection in a laminar regime in a room heated by the technique of a Trombe wall adapted to the site of the city of Béchar (south of Algeria),in a typical winter day. Draoui et al [4] presented the study of natural convection in the transient laminar regime within an uncultivated bottom-heated tunnel greenhouse (heated by flux). Zouiri et al [5] processed the numerical analysis of the natural laminar convection within a square cavity whose vertical walls are maintained at a constant temperature, horizontal walls are thermally insulated , with heat source placed in contact with lower wall. Valencia and Frederick [6] presented a numerical study on the natural convection of air in square cavities with vertical walls half adiabatic. Abourida et al [7] studied numerically the natural laminar convection in a square enclosure subjected to different modes of heating by the sides. Temperature of heated wall varies sinusoidal over time. Penot and Dalbert [8] studied numerical modeling of natural convection flows that develop within a rectangular cavity, heated at constant temperature and open on one of its faces.

Many researches have been performed on natural convection between two vertical parallel plates [9, 10]. Other researches carry out on the ventilation system [11,12,13]. Dubovsky et al [13] perform a study on heat transfer inside a ventilated enclosure. The enclosure is heated by an horizontal downward-facing constant temperature hot plate. Three main approaches are used: (1) temperature measurement which is performed by thermocouples, (2) flow visualization which is performed by using the smoke of incense sticks and (3) numerical simulation.

In this paper, we try to simulate a simplified model for heating and ventilating a room in a passive way by studying Natural convection in a square cavity.

2. Mathematical model

Natural convection caused by heat transfers in a square enclosure have been extensively studied both theoretically and experimentally.

2.1 Governing equations

In fluid mechanics, assuming that the fluid is a continuous medium, Newtonian and incompressible, the flow is unsteady and bi-dimensional. It is important to note that, the physical properties of the fluid are constant except the density which obeys the approximation of Boussinesq in the term of the Archimedes thrust. Which leads to its implication as a driving force in the momentum conservation equation. one can use the classical conservation laws to obtain the governing equations. These later can be written in dimensionless form as follow:

2.1.1 Continuity equation

The dimensionless continuity equation can be written as:

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

2.1.2 Momentum equations

The dimensionless momentum equations following x and y can be written as:

$$\frac{\partial u^*}{\partial t^*} + u^* \frac{\partial u^*}{\partial x^*} + \mathrm{v}^* \frac{\partial u^*}{\partial y^*} = -\frac{1}{\rho}\left(\frac{\partial P^*}{\partial x^*}\right) + Pr\left(\frac{\partial^2 u^*}{\partial x^{*2}} + \frac{\partial^2 u^*}{\partial y^{*2}}\right)$$

$$\frac{\partial \mathrm{v}^*}{\partial t^*} + u^* \frac{\partial \mathrm{v}^*}{\partial x^*} + \mathrm{v}^* \frac{\partial \mathrm{v}^*}{\partial y^*} = -\frac{1}{\rho}\left(\frac{\partial P^*}{\partial x^*}\right) + Pr\left(\frac{\partial^2 \mathrm{v}^*}{\partial x^{*2}} + \frac{\partial^2 \mathrm{v}^*}{\partial y^{*2}}\right) + Pr.Ra.T^*$$

Where, Pr and Ra are Prandtl number and Rayleigh number respectively.

2.1.3 Energy equation

The dimensionless energy equation can be written as:

$$\frac{\partial T^*}{\partial t^*} + u^* \frac{\partial T^*}{\partial x^*} + \mathrm{v}^* \frac{\partial T^*}{\partial y^*} = \left(\frac{\partial^2 T^*}{\partial x^{*2}} + \frac{\partial^2 T^*}{\partial y^{*2}}\right)$$

For solid, this equation can be written, as:

$$\frac{\partial T^*}{\partial t^*} = \frac{\alpha_{solid}}{\alpha_{fluid}}\left(\frac{\partial^2 T^*}{\partial x^{*2}} + \frac{\partial^2 T^*}{\partial y^{*2}}\right)$$

Where,α is the diffusivity and equals to: $\frac{\lambda}{\rho C_p}$

3. Problem description and numerical simulation

3.1 Description of the problem

In this work we are interested in the study of natural convection in a square cavity. The studied configuration is a square geometry of dimensional (1x1) contained a vertical wall. This wall is made of concrete, the fluid inside the cavity is air. The vertical cavity walls are cold and the horizontal walls are adiabatic.

In our study, we are interested in two main phenomena:(1) passive heating and (2) passive Ventilation.

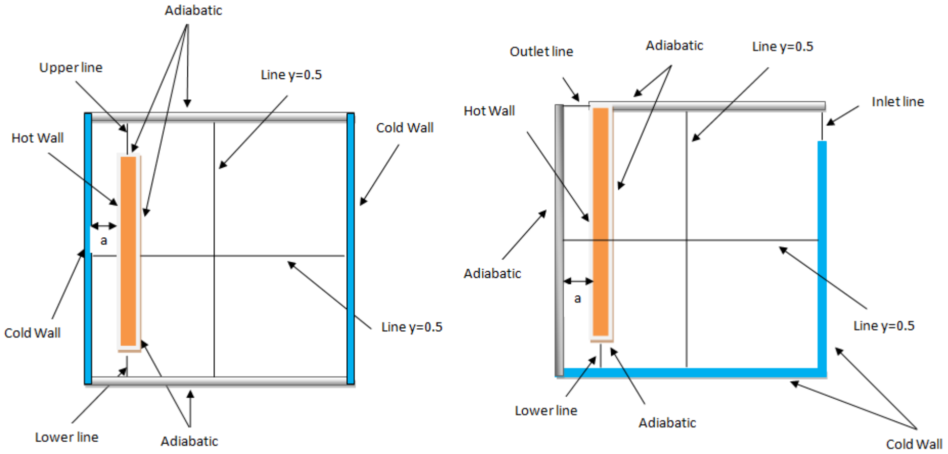


Figure 1. Configuration for passive heating (left) and ventilation (right)

3.1.1 Configuration for passive heating

For passive heating we consider a closed square cavity contain a wall with two opening in top and bottom. The Trombe wall is positioned at a distance (a=air gap) from the left wall. The wall is maintained at warm temperature (Tc) in its left face, and the other faces are adiabatic. The two opening are considered for circulating the fluid in cavity.

3.1.2 Configuration for passive ventilation

For passive ventilation we consider a ventilated square cavity contain a wall with one opening in bottom. In order to ventilate the cavity, we create inlet opening at top of right wall for entering air, and outlet opening at left side of top wall (between Trombe wall and left wall) as exit of air. The Trombe wall is positioned at a distance (a=air gap) from the left wall. The wall is maintained at warm temperature (Tc) in its left face, and the other faces are adiabatic.

3.2. Setting and used parameters

The methods and algorithms used for numerical resolution are presented in the following table:

Table 1. Setting and used parameters

	Methods and algorithms of resolution
Discretization	Finite volume method
Coupling (Pressure-Velocity)	SIMPLE Algorithm
Numerical Interpolation scheme	Pressure: Body force weighted
	Momentum: Power law
	Energy: Power law
Under-Relaxation Factors	0.5 for momentum equation
	0.7 for energy equation
	0.3 for continuity equation
Discretized equation system resolution	Gauss–Seidel Iterative method for a linear system
Monitor convergence criteria	10^{-3} for Continuity
	10^{-3} for Momentum
	10^{-6} for Energy

4. Results and discussion

4.1. Introduction

In this study, our objective is to perform numerical simulation of passive heating and ventilation in a square cavity. The problem description is presented in the previous section with different necessary parameters and settings. In this section, we will present the numerical results of different simulations (heating and ventilation).

4.2. Passive heating results

For the passive heating simulation, we will see the effect of the mesh and Rayleigh's number (Ra) on the temperature distribution in the cavity.

4.2.1. Mesh Effect

Different mesh sizes are used (80x80; 120x120; 160x160; 200x200; 240x240;). In Fig.2.a Temperature vs time is traced at the lower point (under the wall, x=0.15, y=0.05). As shown Fig.2,a The temperature variation in time is vary depending on the mesh size used. With meshing (80X80) we found a result far away from the other meshes. It is clear from the same figure that, the more refined mesh we take, the more we converge towards a more precise result, until we reach to very similar result with Mesh 200x200 and Mesh 240x240. Which means that, we reach to the desired convergence with Mesh 200x200. The same result can be concluded from Fig.2.b, in which the Nusselt number is depend on mesh, until reaching Mesh 200x200 where Nusselt number become unchanged after that. These results conduct us to use the Mesh 200x200 in the remaining simulations.

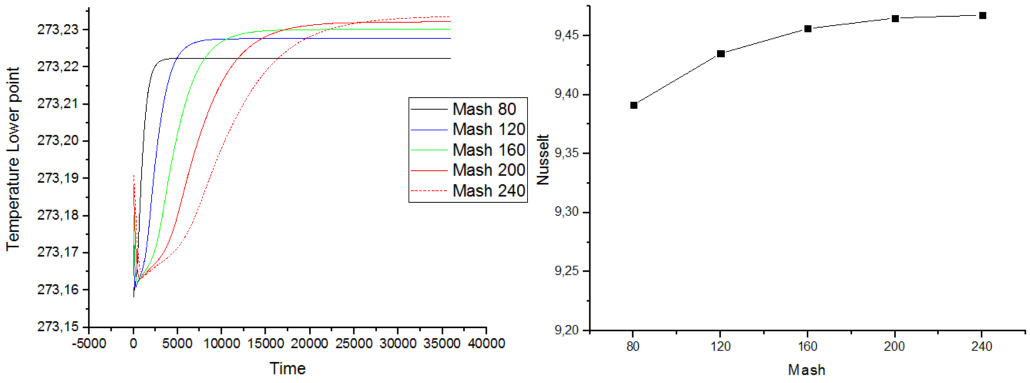


Figure 2. Mesh effect: (a) temperature vs time at lower point and (b) Nusselt number vs mesh.

4.2.2. Rayleigh number effect

Different numbers of Rayliegh are used: (Ra = 10^3; Ra = 10^4; Ra = 10^5; Ra =10^6). Viewing Fig.3, the Rayliegh effect is clear at (t=1800). The temperature propagates rapidly in the case of large number of Rayleigh. The isotherms in Rayliegh (Ra = 10^3) are deformed (curved) and the temperature is relatively low. The greater the Rayliegh number is used, the more the isotherms becomes horizontal lines and the temperature drops layer by layer. The effect of the Rayleigh number is very remarkable in figure 4. As it is shown in Fig.4; Nusselt number, the maximum values of velocities and streamlines increase with the Rayleigh number. The greater the Rayleigh number, the greater the maximum velocity and streamlines values. Figure 5 confirms that the temperature propagation rate and value, and the mass flow of the upper opening variate proportionally with the Rayliegh number.

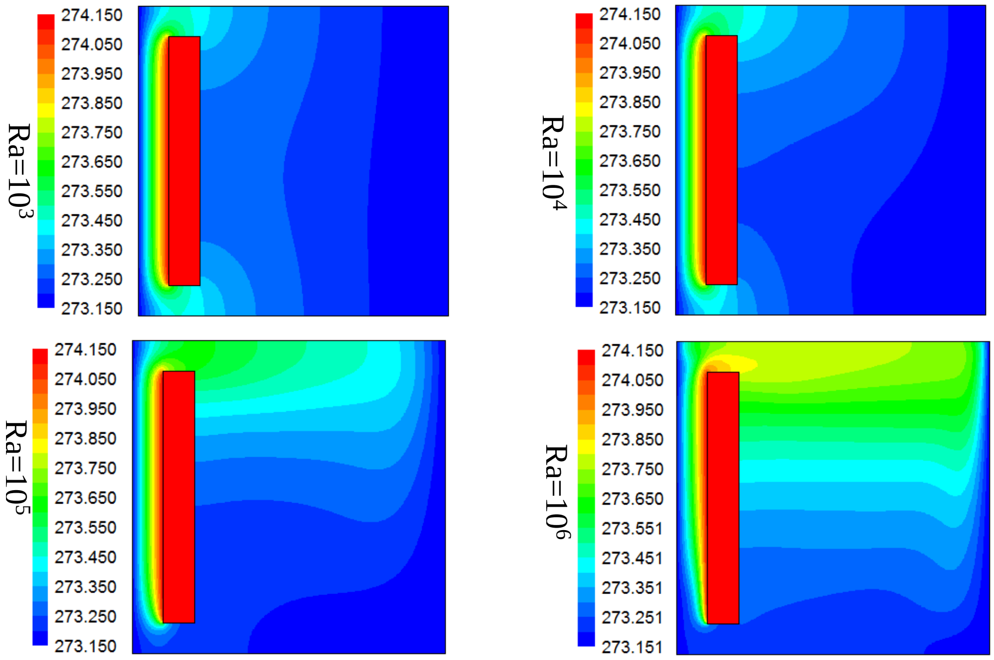


Figure 3. Rayleigh number effect: Temperature distribution in cavity at t=1800.

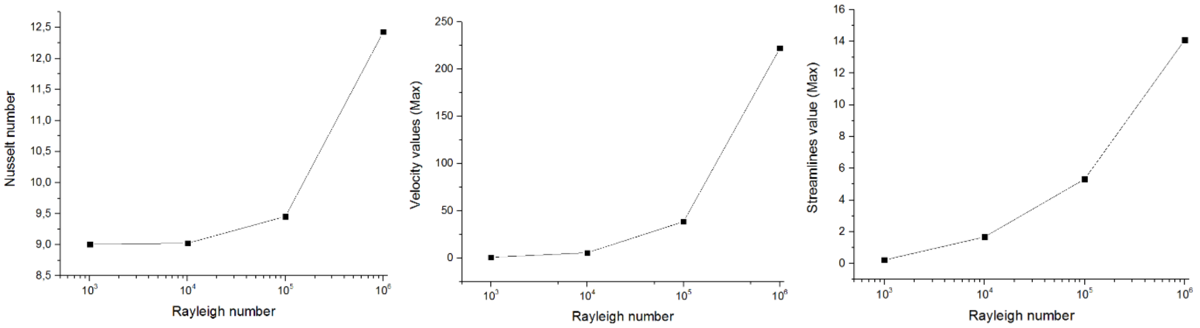


Figure 4. Nusselt number, velocity_max and and streemline valus_max in function of Rayleigh number.

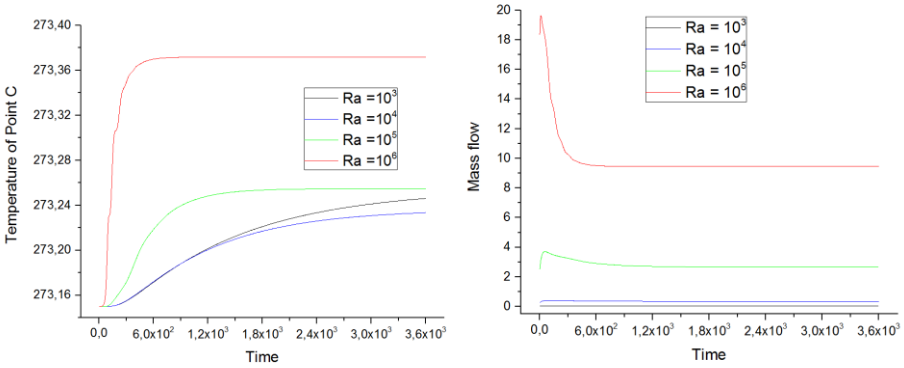


Figure 5. Rayleigh number effect: Temperature of central point and mass flow vs time.

4.3. Passive ventilation results

For the passive ventilation simulation, we will see the effect of the mesh and Rayleigh's number (Ra) on the temperature distribution in the cavity:

4.3.1. Mesh Effect

Different mesh sizes are used (120x120; 160x160 ; 200x200 ; 240x240;). In Fig.6, temperature vs time is traced: (a) at centered point of solar chimney (x=0.05, y=0.5), and (b) at outlet point (x=0.05, y=1). As shown Fig. 6, The temperature variation in time is vary depending on the mesh size used. With meshing (120x120) we found a result far away from the other meshes. It is clear from Fig.6.a and b that, The more refined mesh we take, the more we converge towards a more precise result, until we reach to very similar result with Mesh 200x200 and Mesh 240x240. Which means that, we reach to the desired convergence with Mesh 200x200. The same result can be concluded from Fig.6.c, in which the Nusselt number is depend on mesh, until reaching Mesh 200x200 where Nusselt number become unchanged after that. this results conduct us to use the Mesh 200x200 in the remaining simulations.

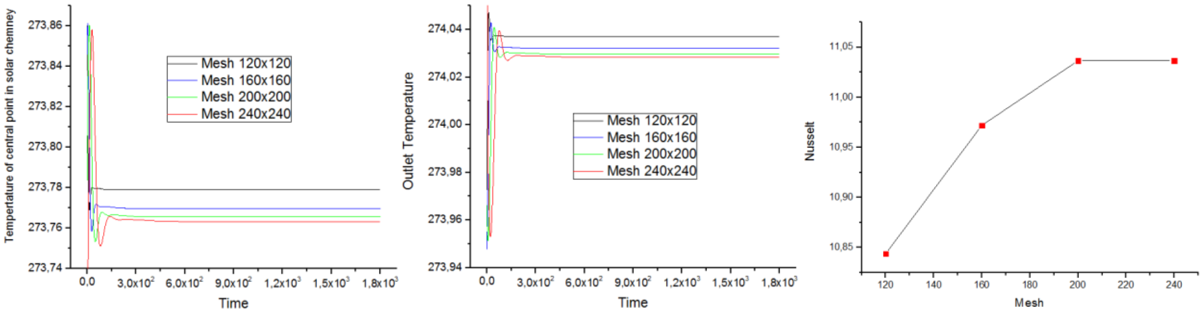


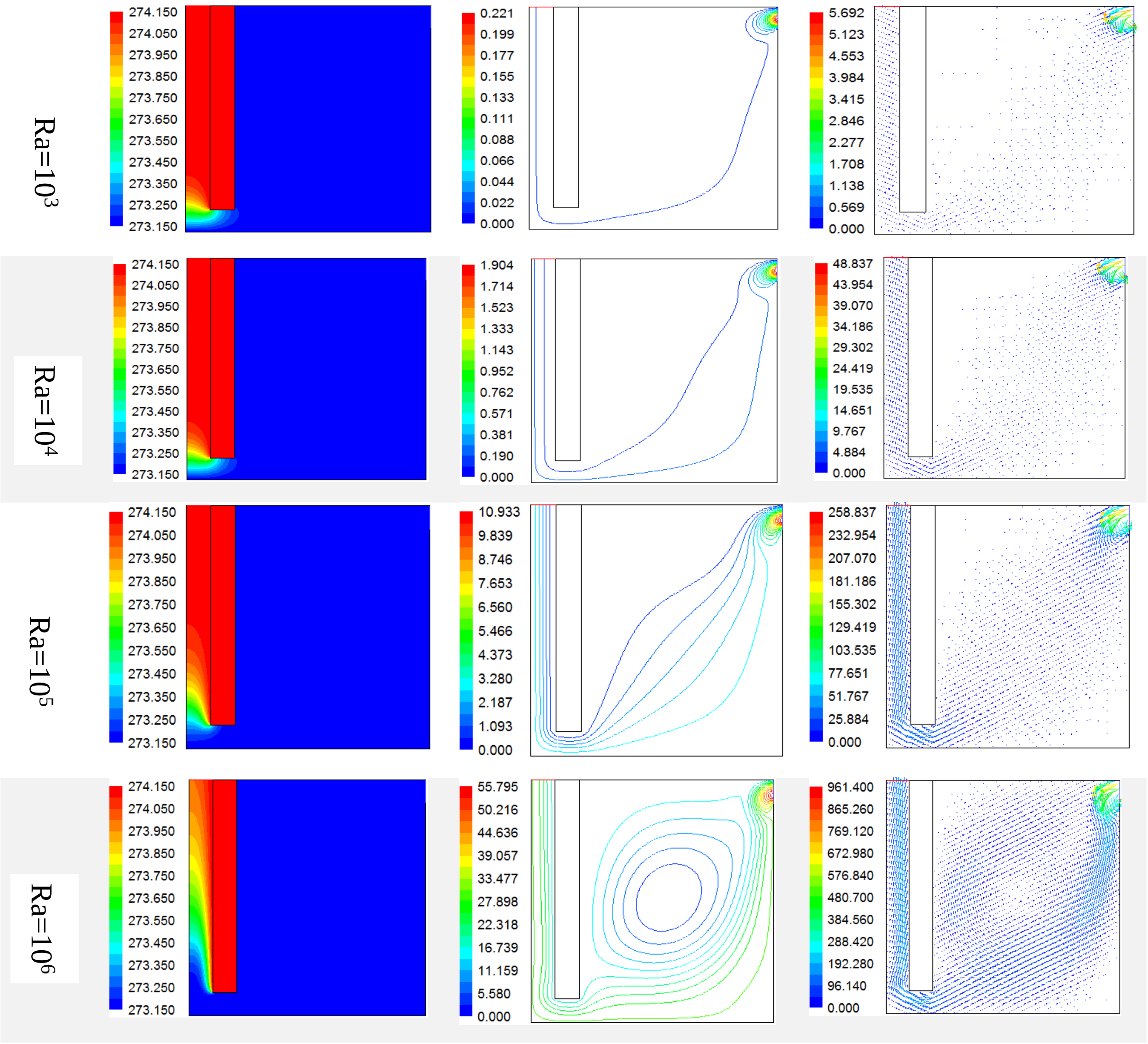
Figure 6. Mesh effect: (a and b) temperature vs time and (c) Nusselt number vs mesh.

4.3.2. Rayleigh number effect

Different numbers of Rayliegh are used: (Ra = 10^3; Ra = 10^4; Ra = 10^5; Ra =10^6). Visualizing Fig.7, the Rayliegh effect is clear at (t=300). The temperature propagates rapidly in the solar chimney and the wall, and no temperature propagation inside the cavity. For small Rayleigh number, the solar chimney is completely heated (in red) contrary to the case with large number of Rayleigh Ra =10^6, where the solar chimney temperature is gradual from bottom to top (outlet). This can be explained by the large air velocity when using large Rayleigh number, which lead to ventilation of solar chimney. The effect of the Rayleigh number is very remarkable viewing the streamlines, velocity vectors (Fig.7) and Nusselt number (Fig.8). The streamlines form illustrates that; air circulate from inlet into outlet. The more the Rayleigh number is large, the more we have many streamlines, which indicate the air circulation. With large Rayleigh number, air enter from inlet, circulate in the whole cavity, and enter in solar chimney through the opening under wall, then upward along the wall toward outlet. This leads to ventilate the whole cavity. The same results can be confirmed through the velocity vectors, which indicate the circulation of air from inlet into outlet. The high density of velocity vectors and their high values are found in whole cavity when using large Rayleigh number. As it is shown in Fig.8; the maximal values of velocities and streamlines increase with the Rayleigh number. The greater the Rayleigh number, the greater the maximal velocity and streamlines values.

5. Conclusion

In this paper, we made a study on natural convection in a square (closed) cavity for both passive heating and ventilation cases. For passive heating, the process of flow in the cavity that has been found can be summarized as follows: The heat emitted by the hot wall is transported by convection to the top of the cavity and moves to the adiabatic top wall. One part goes to the left cold wall and the rest goes to the right cold wall. When the fluid encounters the cold wall, its temperature drops and it moves



(a) Temperature (b) Streamlines (c) Velocity vectors

Figure 7. Rayleigh number effect (t=300).

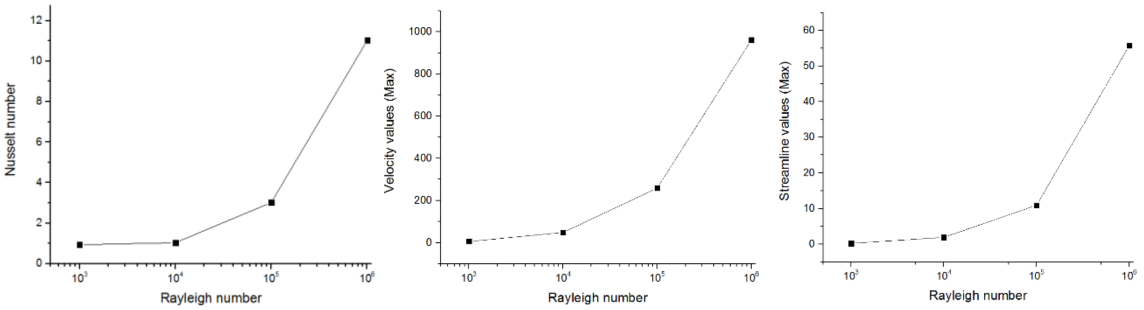


Figure 8. Nusselt number, velocity_max and and streemline valus_max in function of Rayleigh number

downward and goes toward the lower opening in the wall. Fluid circulation in this cycle occurs over time until the fluid flow state becomes stationary.

For the passive ventilation, the process of flow in the cavity that has been found can be summarized as follows: the hot wall heats the air inside the chimney. Due to the difference in air temperature, a density gradient between the inside and outside of the chimney causes an upward movement of air (the buoyancy force). This becomes a driving force and amplifies natural ventilation in the cavity. As result, the air enters from the inlet and encounter the cold wall, where its temperature drops and it moves downward and goes toward the lower opening in the wall. One part circulates inside the cavity and the rest enters through the opening and upward along the walls by the solar chimney effect toward the outlet. This operation leads to ventilate the whole of cavity.

From our study, we can conclude that; the more the mesh is refined, the more one converges towards a more precise result, the temperature propagation rate varies proportionally with the Rayleigh number and the maximal values of velocities and streamlines increase with the Rayleigh number.

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