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RESEARCH ARTICLE

STUDY OF NATURAL CONVECTION IN A 3D CAVITY HEATED BY THE CEILING AT A FIXED RAYLEIGH NUMBER BASED ON HEIGHT

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ABSTRACT

Our objective for this work is to study natural convection in a cavity differentially heated in $3D$. The equations which govern our problem are expressed in a dimensionless form with a calculation procedure based on the finite element method implemented in the COMSOL Multiphysics calculation code. The flow is unsteady turbulent flow. Several numerical studies have been carried out in parallelepiped cavities using the Boltzmann lattice method. In our case, the cavity is heated by the ceiling and the left, right walls and the floor are maintained at the same imposed temperature, while the side walls (front and rear) are assumed to be adiabatic. A validation study of the calculation code was carried out, taking into account the studies carried out by (Hong Wang, 2006). The study on some cavities encountered in the literature was carried out to change the position of the hot temperature and noted the effect of convection in the middle of the cavities, to see the convergence time and the most important convergence time step. We carry out thermal and dynamic studies of natural convection in the cavity K_a. The flow results will be studied in terms of isotherms, flow velocity vectors, streamlines, velocity and temperature isovalues. The effect of thermal radiation from the walls is negligible. The boussinesq approximation is applied. The fluid is Newtonian $P_r = 0{,}71$. The Rayleigh number is $R_a$based on the height of the cavity so it is fixed equal to$R_{aH} = 3{,}34910^{10}$.

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INTRODUCTION

The studies of natural convection in differentially heated cavities have been widely studied in recent years because of their application in various fields such as thermal housing, cooling of electronic components, etc. Thermal convection exerts an important influence on the distribution of temperatures in the internal air volume of a habitat. It is therefore essential in the study of thermal comfort. Several more or less complex geometric configurations have been examined using theoretical, numerical or experimental approaches. This is how authors like (Rouger, 2009) and (F.Djanna, 2011) carried out research on large cavities in three dimensions to obtain turbulent flows which are characterized by Rayleigh numbers between $R_{aH} = 4{,}010^{10}$and $R_{aH} = 1{,}210^{11}$. They were able to establish a correlation between the Rayleigh number based on the height of the cavity and the Nusselt number averaged by $N_{moy} = 0{,}046R_{aH}^{1/2}$. An experimental study on a differentially heated cavity was carried out by (R. Cheeswright, 1986) for a Rayleigh number $R_{aH} = 5{,}010^{10}$in order to show the importance of the boundary conditions and the losses at the level of the horizontal walls. (Salat, 2004) to carry out an experimental study in$3D$in a cavity with aspect ratio 1 by an approach to characterize the flow of natural convection for a Rayleigh number of $R_{aH} = 1{,}510^{9}$. For studies in cavities, (S.XIN, 1995) carried out calculations (DNS-spectral) of turbulent natural convection $R_{aH} \sim 10^{10}$ in a cavity in$2D$filled with air and with an aspect ratio equal to 4. From the point of view of numerical simulation we are today witnessing the appearance of several calculation methods to characterize the turbulent flows of natural convection (X. Trias, 2010) Have studied by an approach $DNS - 3D$, the flow in a differentially heated cavity for a high turbulent Rayleigh number $R_{aH} \sim 10^{11}$. The authors find the gold of the study that a heart moves with oscillating isotherms characterizing the gravity waves at the center of the cavity. However, the method $2D$ is not truly representative of physical reality. For this reason, we study the flow in a parallelepiped cavity in three dimensions with the commonly used finite element method implemented in the COMSOL Multiphysics calculation code. Our work is based on an unsteady turbulent flow. The temperatures are isothermal, and the Radiation of the cavity is assumed to be negligible, the fluid is incompressible Newtonian.

Modeling: This is a cavity of height $H = 3m$, depth $P = 0{,}85m$ and width $L = 1m$. The different wall temperatures are imposed T_f and T_C. The study is done in three dimensions with $\Delta T = 15℃ (T_C = 310K et T_f$=295K), the Prandtl number of the air inside the cell is $P_r = 0{,}71$. The reference temperature is taken at

$$T_0 = \frac{T_C + T_f}{2}$$

Air properties are tabulated in the table below at reference temperature and atmospheric pressure.

Table 1. Thermophysical properties of air at the Reference Temperature T_0

T(K)	ρ (Kg/m ^{3})	Cp(J/ Kg.K)	λ (w/ mK)	α (m ^{2}/ s)	η (P_a.s)	ν (m ^{2}/s)
303	1,127	1,013.10 ^{3}	0.0258	23,4.10 $^{-6}$	18,682	16,6.10 $^{-6}$

η (P_a.s): dynamic viscosity; ν (m ^{2}/s): kinematic viscosity
α (m ^{2}/s): thermal diffusivity; λ (w/ mK): thermal conductivity
Cp (J/ Kg.K): specific heat; ρ (Kg/m^3): the density

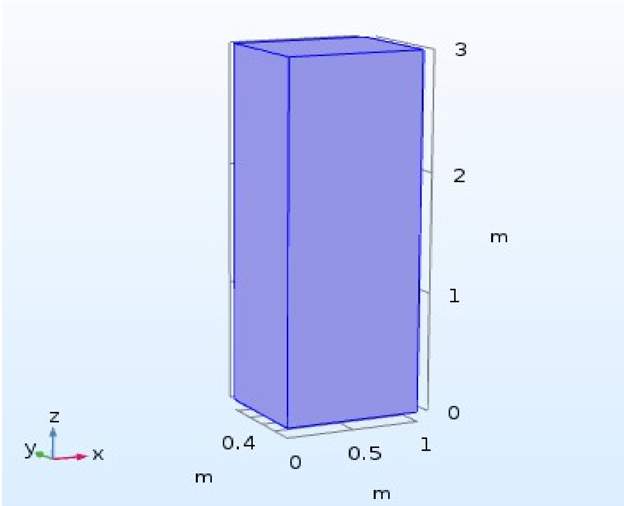


Figure 1. Physical model of the cavity obtained using Comsol 5.3a software intended for the study in 3*D*

Dimensionless equations: Scaling equations consists of transforming the dependent and independent variables into dimensionless variables. These variables will be normalized with respect to certain characteristic values and This makes it possible to specify the flow conditions with a restricted number of parameters to make the solution more general. Let's bring these equations into dimensionless form, to do this let's define the characteristic quantities of the cell and take the height as the reference length (Djedid, 2015).

- Dimensionlesscoordinates$X = \frac{x}{H}$,$Y = \frac{y}{H}$, $Z = \frac{z}{H}$
- Dimensionless temperature $\theta = \frac{T-T_0}{\Delta T}$with $T_0 = \frac{T_C+T_F}{2}$the average temperature of the active walls and $\Delta T = T_c - T_f$
- dimensionless speeds $U = \frac{u}{V_{ref}}$, $V = \frac{v}{V_{ref}}$ $W = \frac{w}{V_{ref}}$with $V_{ref} = \frac{\alpha}{H}\sqrt{Ra_H}$
- Rayleigh number $Ra_H = \frac{g\beta\Delta T H^3}{\alpha \nu}$
- Prandtl number $P_r = \frac{\nu}{\alpha}$

The driving pressure at the reference state (ρ_0, T_0)***:*** $P' = P + \rho_0 g z$

In a Cartesian Reference

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} + \frac{\partial W}{\partial Z} = 0 \quad \text{equation [1]}$$

1-2 momentum conservation equations

Along the x axis: the mass forces are zero, we therefore have:

$$\frac{\partial U}{\partial \tau} + U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} + W\frac{\partial U}{\partial Z} = \frac{-\partial P'}{\partial X} + \frac{P_r}{\sqrt{Ra_H}}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2} + \frac{\partial^2 U}{\partial Z^2}\right) \text{equation [2]}$$

According to the y axis:

$$\frac{\partial V}{\partial \tau} + U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} + W\frac{\partial V}{\partial Z} = \frac{-\partial P'}{\partial Y} + \frac{P_r}{\sqrt{Ra_H}}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2} + \frac{\partial^2 V}{\partial Z^2}\right) \text{equation [3]}$$

Along the z axis:

$$\frac{\partial W}{\partial \tau}+U\,\frac{\partial W}{\partial X}+V\,\frac{\partial W}{\partial Y}+W\,\frac{\partial W}{\partial Z}=\frac{-\,\partial P'}{\partial Z}+\frac{P_r}{\sqrt{Ra_H}}\left(\frac{\partial^2 W}{\partial X^2}+\frac{\partial^2 W}{\partial Y^2}+\frac{\partial^2 W}{\partial Z^2}\right)+P_r\theta \text{ equation [4]}$$

For a three-dimensional system (0, x, y, z):

$$div\left(\overrightarrow{grad}\,T\right)=\left(\frac{\partial^2 T}{\partial X^2}+\frac{\partial^2 T}{\partial Y^2}+\frac{\partial^2 T}{\partial Z^2}\right) \text{ equation [5]}$$

$\alpha=\frac{\lambda}{\rho_0 C_P}$ Is the thermal diffusivity of the fluid

The energy equation is

$$\frac{\partial \theta}{\partial \tau}+U\,\frac{\partial \theta}{\partial X}+V\,\frac{\partial \theta}{\partial Y}+W\,\frac{\partial \theta}{\partial Z}=\frac{1}{\sqrt{Ra_H}}\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}+\frac{\partial^2 \theta}{\partial Z^2}\right) \text{ equation [6]}$$

Thermal Boundary Conditions: There are several types of thermal boundary conditions which are available in the Comsol Multiphysics software: the heat flow can be imposed on the walls, the convective heat transfer, the imposed temperature, external radiative heat transfer, there is the combination of two heat transfers, by convection and by radiation or mixed convection.

For our study there is:

1- The two horizontal walls are maintained at a temperature gradient of $\Delta T=15K$. The cavity is heated from above. The vertical walls (left and right) and the floor are subjected to a constant temperature equal to the cold temperature. The other walls (front and rear) are assumed to be adiabatic and a dynamic condition of adhesion to the walls is imposed ($u=v=w=0m/s$).
2- The walls of our cavity are maintained at different temperatures.

Warm wall ceiling $\theta\left(Z=\frac{1}{A_Y}\right)=0{,}5\ \forall\,(X,Y)$

Cold wall floor $\theta(Z=0)=-0{,}5\ \forall\,(X,Y)$

Cold left wall $\theta(X=0)=-0{,}5\ \forall\,(Z,Y)$

Right cold wall $\theta\left(X=\frac{1}{A_Y}\right)=-0{,}5\ \forall\,(Z,Y)$

Rear wall $\left(\frac{\partial\theta}{\partial Y}\right)_{Y=\frac{1}{A_r}}=0\quad\forall\,(X,Z)$

Front wall $\left(\frac{\partial\theta}{\partial Y}\right)_{Y=0}=0\quad\forall\,(X,Z)$

Mesh representation mode: A good quality mesh has a serious impact on the convergence, the precision of the solution and especially on the calculation time. It allows you to obtain a precise calculation result. Good quality is based on the minimization of elements presenting distortions and on good resolution in regions presenting a strong temperature gradient (boundary layers, shock waves, etc.). In the case of our study, the model of our cavity was meshed with a mesh of predefined size Coarse including 133550 tetrahedra. We opted for a uniform mesh in all three horizontal and vertical directions X, Y and Z as well as the COMSOL Multiphysics calculation code was developed as a calculation program for a segregated convergence criterion varying between$10^{-5}$with 10^5a time step of 10 spread over 3600s.

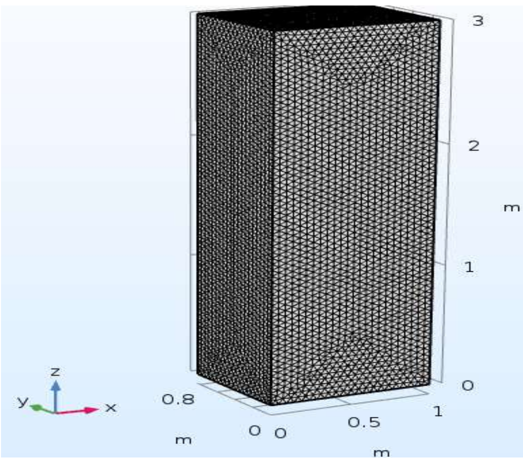


Figure 2. Coarse mesh adopted for the study

RESULTS AND DISCUSSION

In order to verify the accuracy of our numerical work, a validation of the numerical code is carried out by taking into account certain numerical and experimental studies which exist in the literature. Indeed, we will validate our work with the results of (Hong Wang, 2006) H. wang in the case of a square cavity containing air whose four front, rear, ceiling and floor faces are assumed to be adiabatic but at uniform temperatures. The left and right vertical faces are differentially heated to $\Delta T = 10K$. The validation curves are representedfollowing the study.

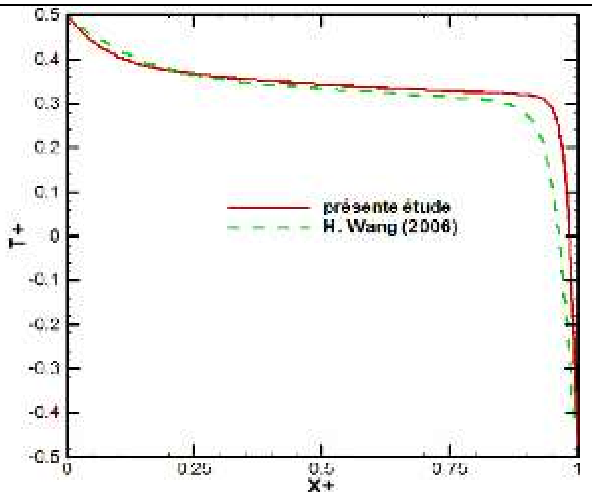


Figure a: comparisons of high wall temperature profiles (Hong Wang, 2006)

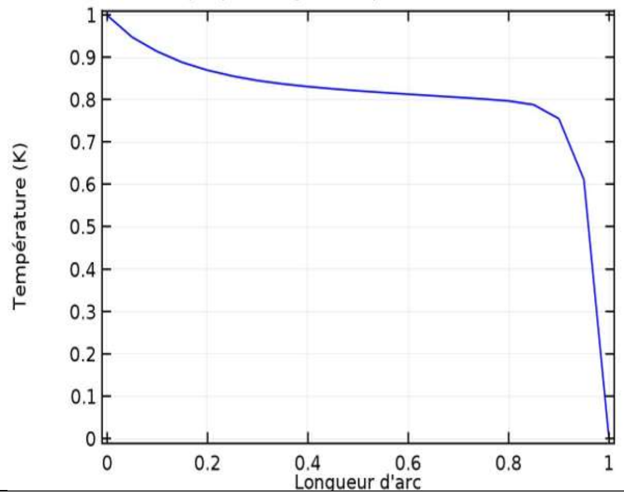


Figure b: upper wall temperature (the present work)

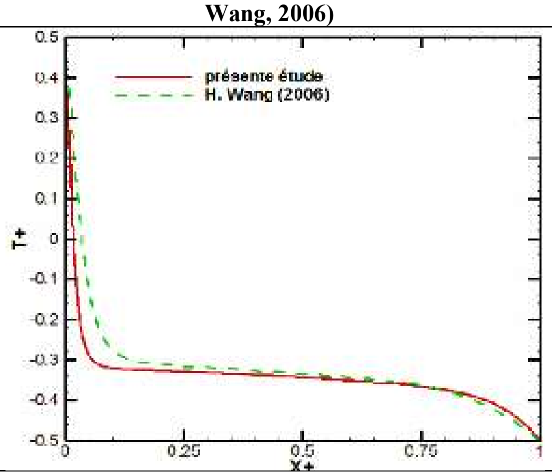


Figure c: comparisons of temperature profiles on the lower wall (Hong Wang, 2006)

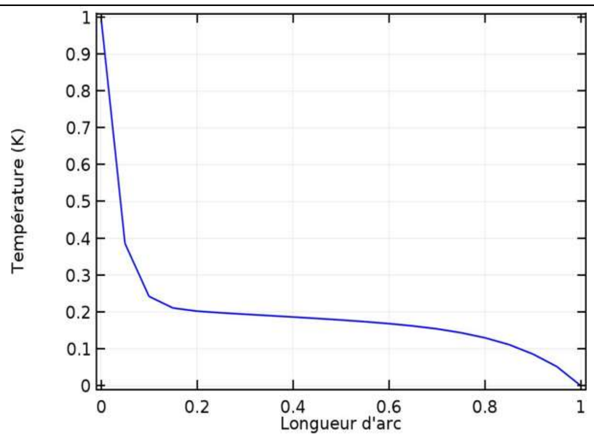
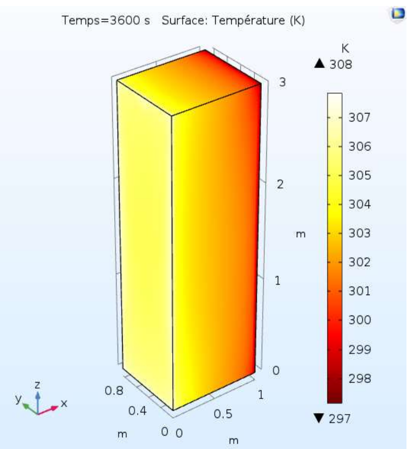


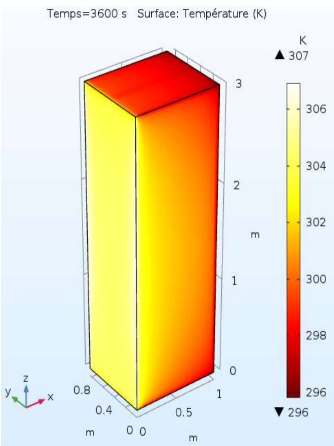
Figure d: temperature of the lower wall (the present work)

Figure 3. Validation curves

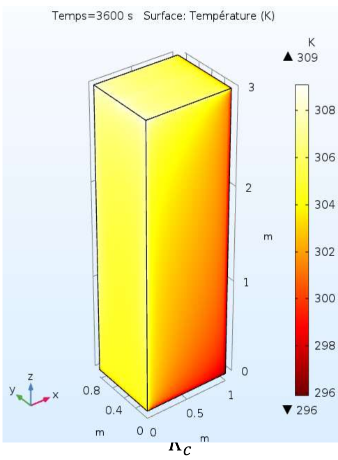
The five configurations studied in relation to the different position of the hot temperature: We carried out the simulation of natural convection in the cavities in accordance with their arrangement already reported. After introducing the air properties into the Comsol 5.3a calculation code, we obtain the temperature profiles listed in the table below. Our results will be presented in the form of a streamline and an isotherm. The temperatures are isothermal, and the Radiation of the cavity is assumed to be negligible, the fluid is incompressible Newtonian



K_a



K_b



K_c

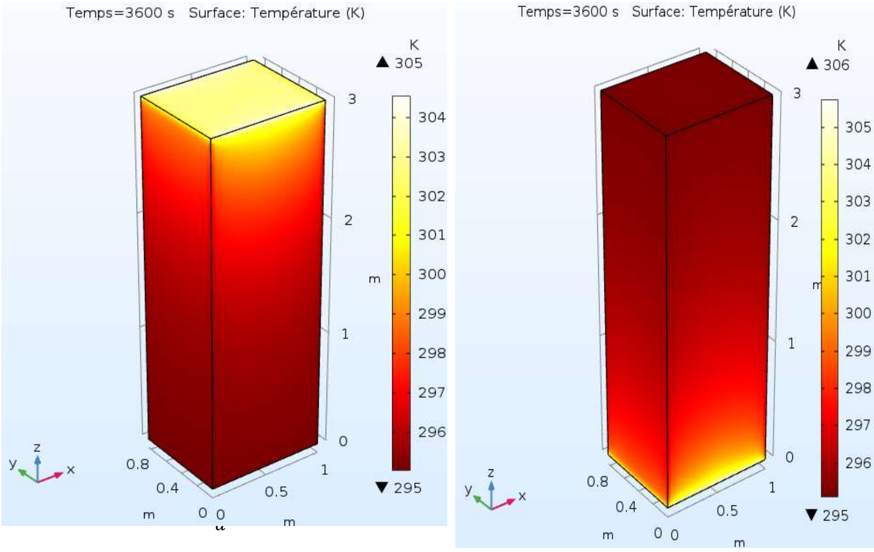


Figure 4. Temperature profile of the different cavities for$R_{aH} = 3,34910^{10}$

Figures 4, K_a, K_b , K_c, K_d, $K_e$above represent the temperature surfaces of the different configurations obtained by the Comsol 5.3a software after the introduction of all the physical properties of the air taken at the reference temperature. The temperature profiles are shown in the table above. We observe on these five cavities the heat flows caused by the variation in temperature inside the differentially heated cavities. In natural convection, we noted that during steady state numerical simulation, convergence is difficult to achieve. This phenomenon is explained by the fact that the velocity and pressure fields essentially depend on the temperature field. For this reason, we adopted in our study for turbulent flow in unsteady regime, that is to say that we make the solution converge at each time step. This leads us to carry out several tests in cavities in relation to the arrangement of the temperature $T_C$of the walls but the difficulties of making the solution converge in turbulent flow and steady state remains the same. The segregated solver always comes out with an error so this forces us to apply the temporal regime. Because of the temperature difference that exists between the isothermal walls, a natural convection flow is created which develops inside the cavities. There is no heat source inside these cavities. A single cavity will be the subject of our study because a cavity heated by the ceiling is rarely encountered in the literature and the convergence time is the best compared to other cavities. The temperature imposed on the vertical walls and the floor T_f is that of the experimental study (Slatini Yassine, 2016) and subsequently, this cavity will be the subject of the study in forced convection because of the arrangement of these cold walls.

Configuration Temperature Profile K_d

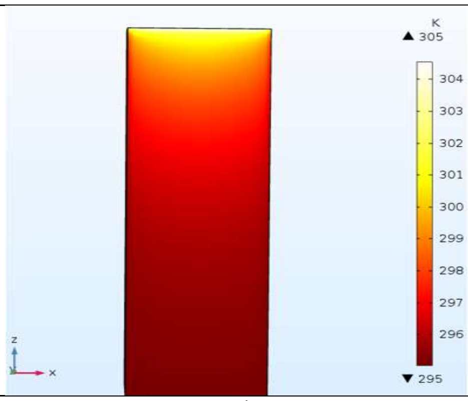
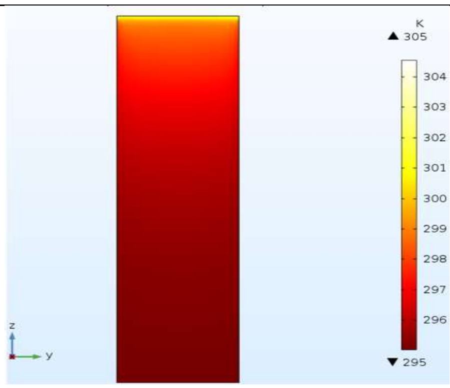
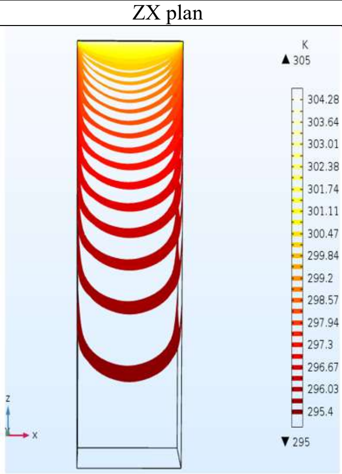
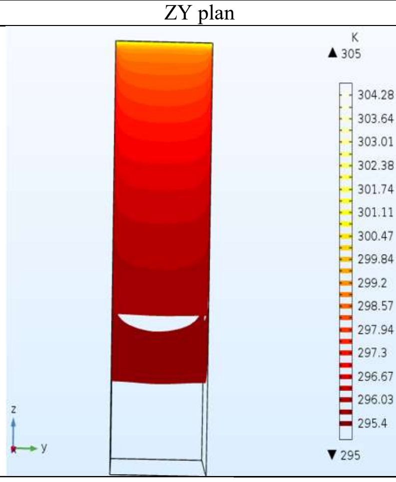
	
ZX plan	ZY plan
	
ZX plan	**ZY plan**

Figure 5. Isosurfaces(K_d) and the (K_d) temperature isotherms of the cavity heated by the ceiling at $R_{aH} = 3,34910^{10}$

The instantaneous average temperature field is represented in the cavity heated from above in view in the ZX and ZY plane of the cavityK_d for the Rayleigh number$R_{aH} = 3{,}349 10^{10}$. We observe stacking of isotherms caused by the drop in the hot temperature which goes down to the cold wall. The heat flows move, push to the point where they disrupt the vertical boundary layers near the cold vertical walls opposite. The effect of the mixing of these vortices is to eject hot or cold fluids from the isothermal walls, which allowed the presence of hot isotherms in the upper part and lower cold regions. The heat recovered from the heated part of the cavity is transported by convection essentially by the left and right walls of the cavity; this is evacuated symmetrically downwards in the middle of the cavity, which explains the relatively high temperature in the central part of the cavity. The physical phenomena are present in particular in the zone of the boundary layer characterized by the existence of strong gradients in the upper parietal zones. In the lower half of the cavity, the temperature is relatively low up to 295K.

Study of the dynamic field in natural convection: The velocity field characterizes the dynamic behavior of the air flow in the cavity.

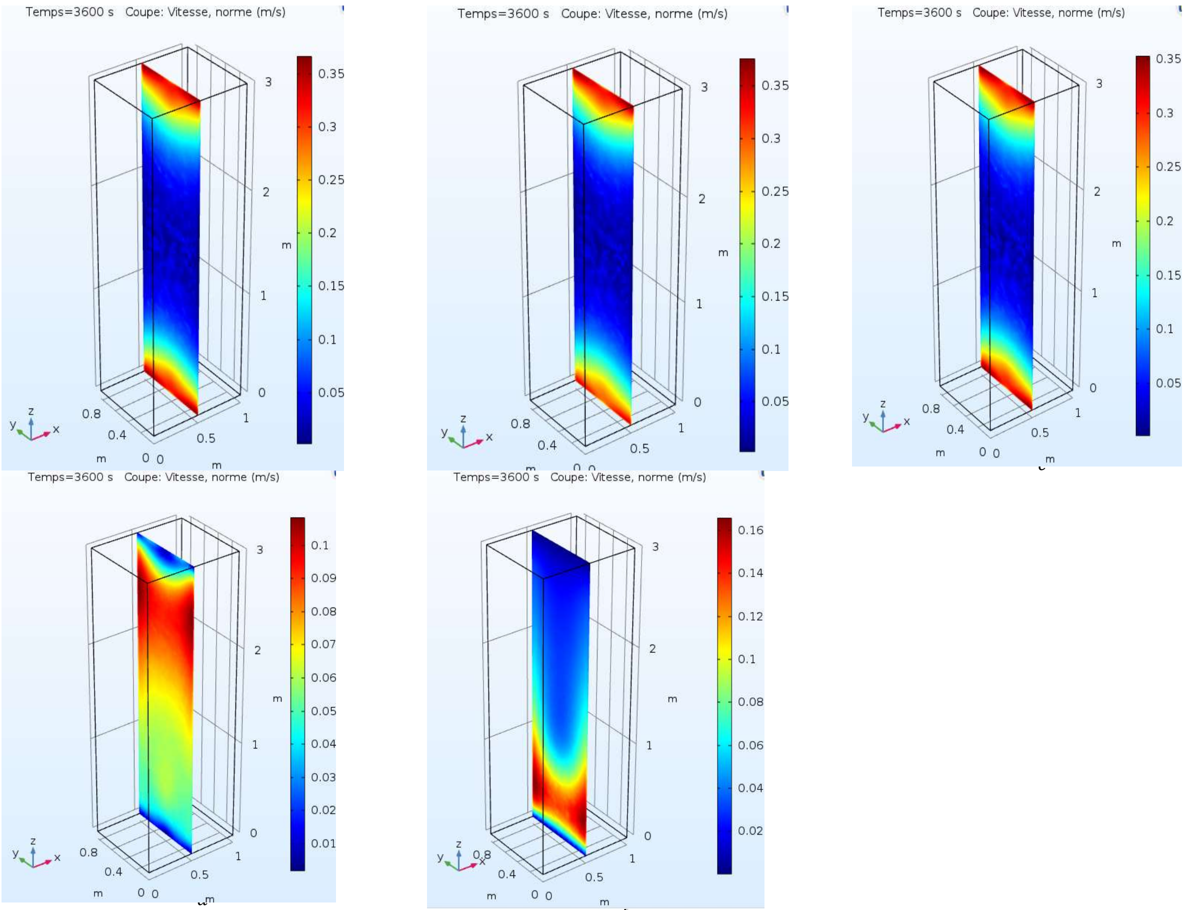


Figure 6. Speed section in the plane$X = \frac{L}{2} = 0,5m$ for all five configurations $R_{aH} = 3,349 10^{10}$

The configurations, K_a, K_b, K_c, K_d, $K_e$in Figure 6, represent the speed section in the plane X=L/2=0.5m. We observe that the highest flow speeds 0.35m/s are located in the lower and upper horizontal walls of the cavities K_a, K_b, K_c. This is due to the warm temperature provision. These speeds are mainly located in the 2.20m≤Z≤3m and 0≤Z≤0.2m portions of these first three configurations. We also note that these are only the configurations whose left vertical walls are at $T_C$and right are at T_f. In the interval 0.20m≤Z≤2.40m, following the vertical, the flow speed is quite low for the configurations $K_a K_b K_c$. For the K_d and K_e configurations, the opposite phenomenon occurs on the horizontal walls because of the low flow speeds. We see that near the adiabatic walls (front and rear wall) a slight increase in speed between 1m≤Z≤2.5m for K_d and 0.12m≤Z≤0.85m for K_e This remark is made for these two configurations where K_d is heated by the ceiling and K_e is heated by the floor. We notice that the left and right walls of these two configurations are subjected to a temperature T_f

Field of velocity vectors in the cavity(K_d)

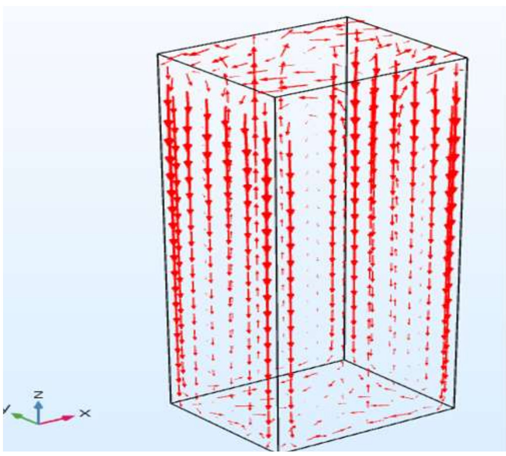
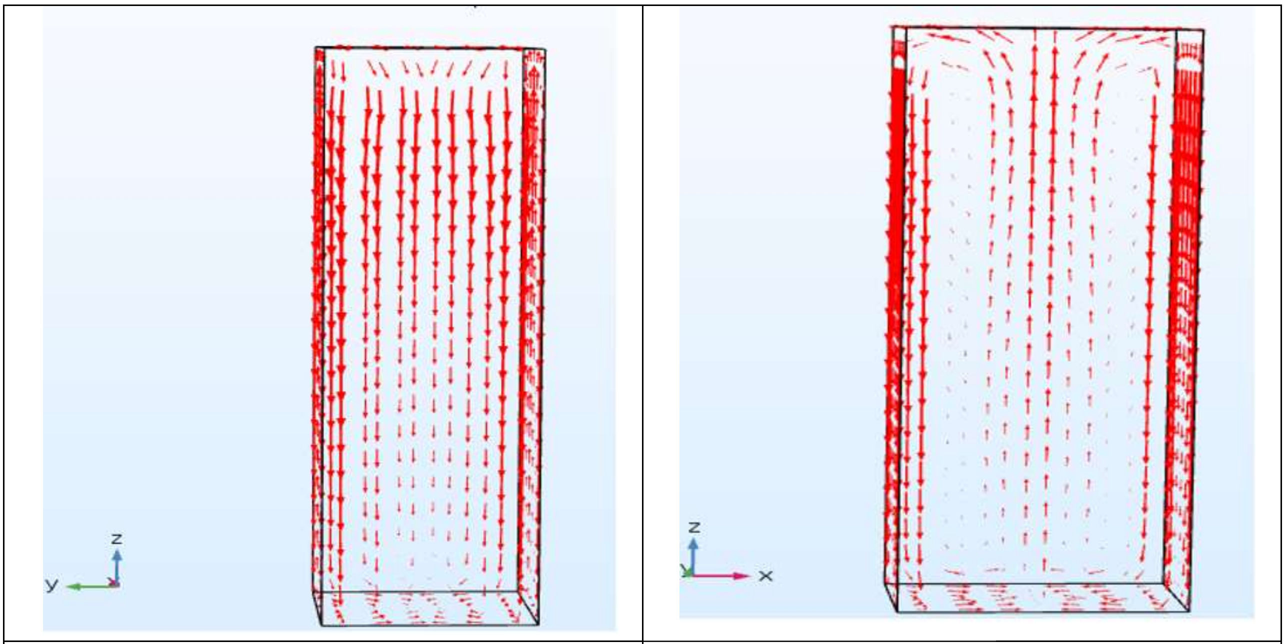


Figure 7. Velocity field of the cavity heated from above (K_d)

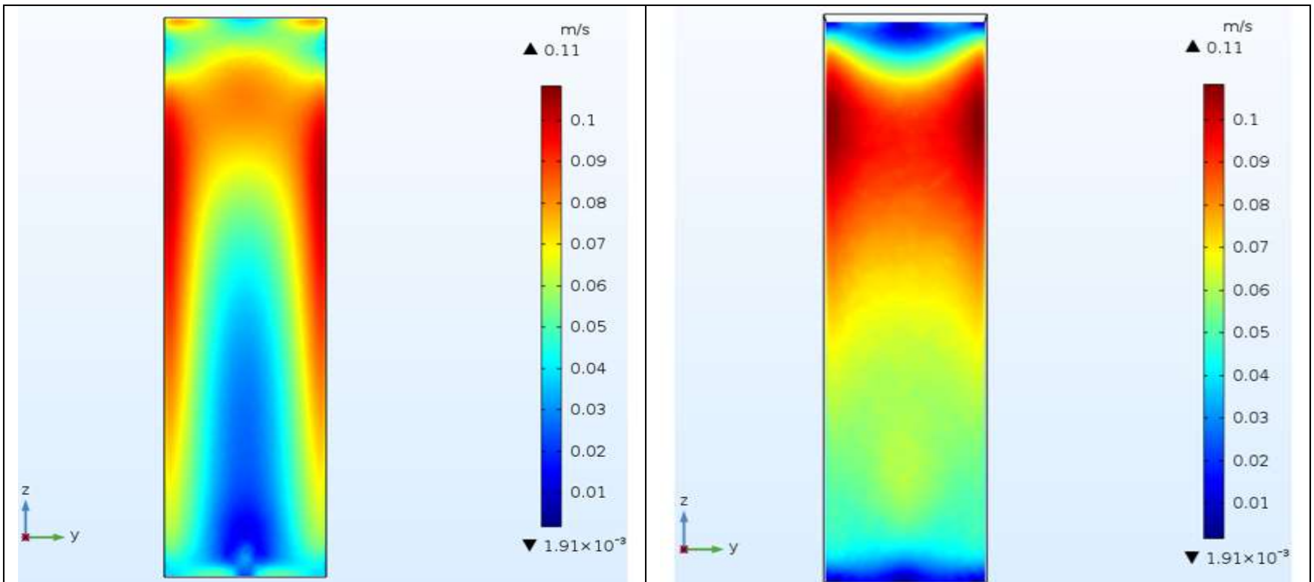


K_d: velocity field in the planeZYIn 3D	K_d: velocity field in the planeZXIn 3D

Figure 8. Velocity vector field of the flow configuration$K_d$in the plan ZY and ZXin$R_{aH} = 3,34910^{10}$

The flow consists of two main symmetrical cells. The two counter-rotating cells close to the vertical walls of the cavity are mainly maintained by buoyancy forces. Visibly in the cavity on the ZX plane, we see that the speed vectors in the middle form a parallel line going up towards the ceiling and share the directions to the left and to the right after reaching the ceiling. Their directions consist of following the cold vertical walls to the floor as indicated by their direction in the cavity according to 3D front view. This is explained by the fact that the air near the ceiling acquires a variation in density caused by the temperature difference between the walls and moves as a result of convective movement up to the floor. This cavity heated by the ceiling shows that the flow velocity vectors are shared in two directions passing close to the two vertical cold walls at $T_f$to descend to the floor before rising through the middle of the cavity after mixing with the cold fluids of the floor. The fluids from the cold wall tend to descend to the floor before rising through the middle and then moving, forming two cells in the clockwise and trigonometric directions of the cavity.

Cavity velocity profilesK_d



K_d: speed profile seen from left and right of the cavity heated by the ceiling in$3D$	K_d: speed profile right in the middle of the cavity heated by the ceiling ($X = \frac{L}{2} = 0,5m$)

Figure 9. Velocity profile of K_d configurations at $R_{aH} = 3,34910^{10}$

These figures correspond to the velocity profile in the plane ZY cold wall on the left and the middle of the cavity $K_d$at X=L/2=0.5m. We observe a rather remarkable speed close to the vertical walls at 0.11m/s. This same speed is also observed at the top of the upper wall of the cavity. The flow presents fairly high speeds close to the adiabatic walls at a maximum value of around 0.11m/s against the lowest value of around 0.01m/s. We are witnessing a transfer of heat by convection due to the movements of the particles caused by the difference in temperatures in this differentially heated cavity.

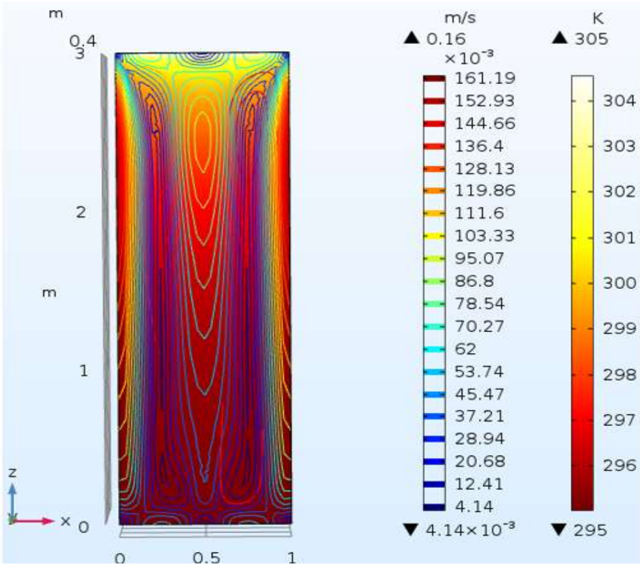


Figure 10. Current lines, velocity isovalues and temperature at $R_{aH} = 3,34910^{10}$

The analysis of Figure 11 shows that on the ZX plane we witness velocity isovalues and current lines. We observe that in the vicinity of these two vertical walls, the flow speeds are relatively low (0.161m/s). Heated by the ceiling, the heat from the hot horizontal wall descends and the flow velocities are relatively low up to 0.0041m/s. The variation in flow speed is due to the variation in fluid density caused by the difference in wall temperature. We notice that at the bottom of the ceiling, there is a deviation in the direction of the flow of the particles in two, following the clockwise direction and the counterclockwise direction. This orientation forms two large rotating cells that are packed close to the cold vertical walls. We note the formation of small circulations in the middle of the cavity between 1.5<Z<2,8. The isovalues of speeds and current lines change shape and become elliptical from the top of the ceiling, in the middle and down to the floor so the effect of convection is more pronounced. There is a low flow speed close to the floor due to the high density of the fluid and this phenomenon can be explained by the low temperature of the lower wall.

CONCLUSION

In this chapter, we have mathematically described the flow of natural convection in a cavity whose walls are isothermal. The numerical applications have been described in order to carry out the simulation and obtain the results which are discussed. A validation code was found by comparing our results to those of (Hong Wang, 2006). The flow in the cavity is unsteady turbulent. We found that the study of natural convection in a cavity differentially heated by the ceiling generates the flow of natural convection as a result of the temperature difference existing in the cavity. The cavity K_d forms recirculations visible by the speed vectors, one of which follows clockwise and the other counterclockwise. Isotherms, streamlines, and velocity vectors are observed. This cavity K_d will be the subject of a study of mixed convection.

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