Recueil De Mécanique
Centre Universitaire
El Wancharissi de Tissemsilt

Research Paper DOI : 10.5281/zenodo.2581476 Open access

Thermo-convective structure of a non-Newtonian fluid at different Rayleigh numbers and temperature gradients in a confined cavity

Structure thermo-convective d'un fluide non newtonien à différents nombres de Rayleigh et gradients de température dans une cavité confine

Hamidou BENZENINE[a,b]

[a]*Department of Mechanical Engineering, Institute of Technology. University Center BELHADJ Bouchaib BP 284 RP, Ain Témouchent, 46000, Algeria.*

[b]*Laboratory of Energetic and Applied Thermal (ETAP), Faculty of Technology, B.P 230, University of Tlemcen, 13000, Algeria.*

ARTICLE INFO

Article history:

Received 13 February 19

Received in revised form 28 February 19

Accepted 01 Mars 19

Keywords:

Natural convection; Cavity; Numerical simulation; CFD.

Mots clés:

Convection naturelle; Cavité; Simulation numerique; CFD.

ABSTRACT

The study of heat transfer by natural convection in a square cavity saturated by a fluid is considered. The two vertical walls are heated and cooled and the other two walls are considered adiabatic. A numerical study of this phenomenon was conducted, by solving the complete system of governing equations by a fluent computer code and using the Boussinesq approximation. In order to verify the validity of our results, a numerical confirmation with references is thus obtained. The variation of the dynamic and thermo-convective structures of an airflow was analyzed for an aspect ratio configuration equal to one and for different number of Rayleigh and temperature gradients. The study also confirmed the proportionality of mean Nusselt number and mean heat flux with temperature gradient and Rayleigh number.

RÉSUMÉ

L'étude de transfert de chaleur par convection naturelle au sein d'une cavité carrée saturée par un fluide est considérée. Les deux murs verticaux sont chauffés et refroidis et les deux autres murs sont considérés adiabatiques. Une étude numérique de ce phénomène a été menée, en résolvant le système complet d'équations gouvernantes par un code de calcul fluent en utilisant l'approximation de Boussinesq. Afin de vérifier la validité de nos résultats, une confirmation numérique avec des références est ainsi obtenue. La variation des structures dynamique et thermo convectif d'un l'écoulement d'air a été analysé pour une configuration de rapport d'aspect égal à un et pour différents nombre de Rayleigh et gradients de température. L'étude a également confirmé la proportionnalité du nombre de Nusselt moyen et le flux de chaleur moyen avec le gradient de température et les nombre de Rayleigh.

1. Introduction

In recent years, considerable research effort has been devoted to the study of heat transfer by natural convection

* *Corresponding author.*
E-mail address: b.hamidou@yahoo.fr

induced in a cavity saturated with fluid. The interest for these natural convection phenomena is due to the many potential applications in engineering. Among these, mention may be made:

Natural convection in fluid environments such as: growth of crystals for the semiconductor industry, solar collectors, double glazing in homes and buildings, cooling of electronic components, insulation building thermal, liquid gas storage and dispersal of pollutants and heat discharges in tanks [1-5].

Natural convection in porous media such as: drying processes, underground disposal of nuclear waste, thermal insulation, geophysical flow, heat exchangers and design of nuclear reactors [6-11].

In the abundant literature that has been devoted to the study of natural convection in cavities, the differentially heated square and rectangular cavities are undoubtedly the configurations that have attracted the most attention from the scientific community.

Paradoxically, few studies deal with the effects of Rayleigh and the temperature gradient applied to the walls on the general behavior of the flow and on the exchange of heat within cavities in natural convection regime.

2. Physical system

A square cavity, of width L and height H, with a horizontal temperature gradient was considered; the vertical walls are heated and cooled, while the horizontal walls are considered adiabatic (Figure1)

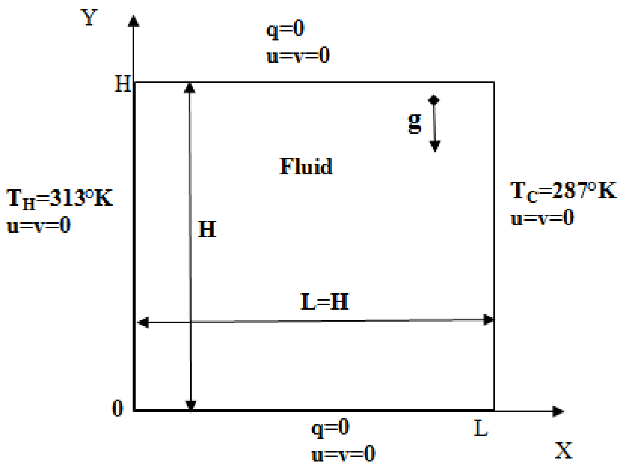


Fig. 1: Representative diagram of the problem.

3. Mathematical model

The resolution of a natural convection problem consists of the determination of the velocity and temperature fields at each point of the domain occupied by the fluid in the cavity. For this purpose, the basic equations governing the flow and heat transfer are established and given by :

- **Continuity equation:**

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

- **Momentum equation:**

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\upsilon\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+g\beta(T-T_f)+\upsilon\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{2}$$

- **Energy conservation equation:**

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\lambda}{\rho C_p}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{3}$$

where : u, v: components of the velocity , p: pressure, ρ: density, g: acceleration of gravity, β: coefficient of expansion, υ: kinematic viscosity, λ : thermal conductivity and Cp is the specific heat of the fluid at constant pressure.

Natural convection flows in the cavity are determined by three governing parameters: The Rayleigh number (Ra), the Prandtl number (Pr) and the aspect ratio (A). They are defined as f0llows:

$$Ra=\frac{gB(T_H-T_C)H^3}{\alpha v}, Pr=\frac{v}{\alpha}, A=\frac{H}{L} \quad 4)$$

The following classical approximations are made:

- The generated flow is laminar,
- The work induced by the viscous and pressure forces is negligible
- Radiant heat transfer is negligible,
- The flow is stationary,
- In this study, a simplifying hypothesis generally accepted by most authors, namely the Boussinesq hypothesis, was used.
- All other thermo-physical characteristics of the fluid are considered constant and defined at the reference temperature T_0

4. Boundary conditions

The boundary conditions used are as follows:

- y = 0 et y = H ; u = v = 0, $\partial T/\partial Y = 0$
- x = 0, u = v = 0, $T = T_H$,
- x = L, u = v = 0, $T = T_C$,

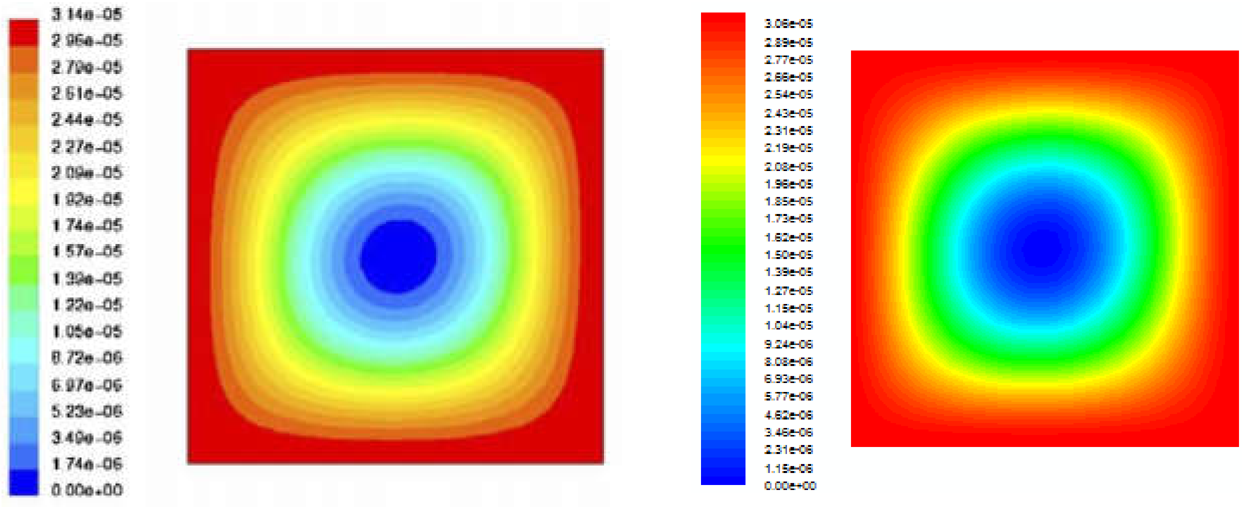
5. Numerical modeling

A Fluent calculation code, based on the finite volume method [12] was used to perform numerical calculations. The discretization of the convective term in the conservation equations is done by a second-order scheme upwind, while the pressure-velocity coupling is treated with the SIMPLE scheme described by Patankar [13]. The optimal computing mesh is built with 4900 quadrilateral elements. Convergence has been ensured by controlling residues of conservation equations by fixing its variations below 10^{-5}

6. Results and discussion

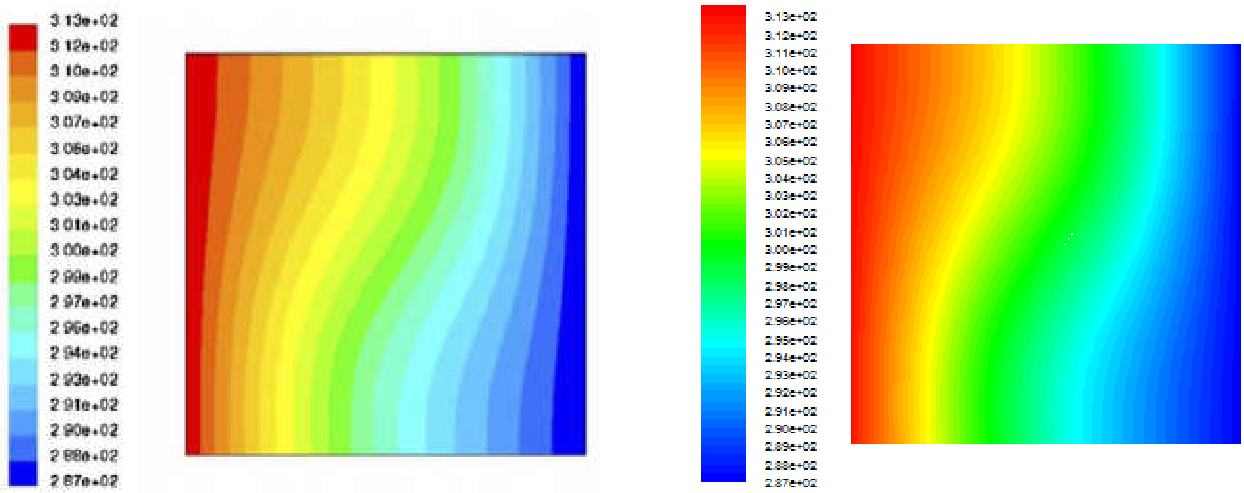
6.1. validation

The work of El Hassan Ridouane and Antonio Campo [14] was chosen as a validation model of our numerical simulation. This work examines the fundamental aspects of natural convective laminar airflow and cavity heat transfer rates. square modified, with two vertical walls heated and cooled and the other two horizontal walls are isolated.Their work is based on the effects of the curved shape in the four walls, on the heat transfer enhancement, and the comparison of the exchange rate between the air flow in a square cavity and a circular cavity.



(a) (b)

Fig. 2: the streamlines for Rayleigh, Ra = 10^3, a) El Hassan Ridouane and Antonio Campo [14], b) simulated result

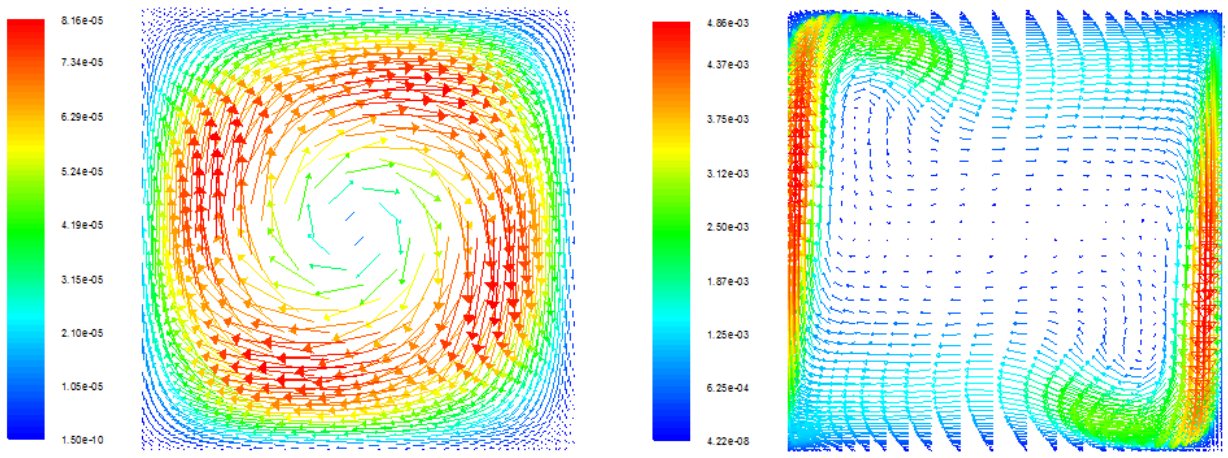


(a) (b)

Fig. 3: Isotherms for Rayleigh, Ra = 10^3, a) El Hassan Ridouane and Antonio Campo [14], b) Simulated result

The same conditions used by El Hassan Ridouane and Antonio Campo [14] were adopted (convection fluid: air, aspect ratio equal to 1, laminar regime, ΔT = 26 ° K, Ra = 10^3. figures 2 (a and b) and figures 3 (a and b) respectively show the streamlinesand the isotherms for a Rayleigh number Ra = 10^3. The comparison shows that there is a qualitative agreement between the results obtained by simulation and given by the reference [14],

6.2. Dynamic structure



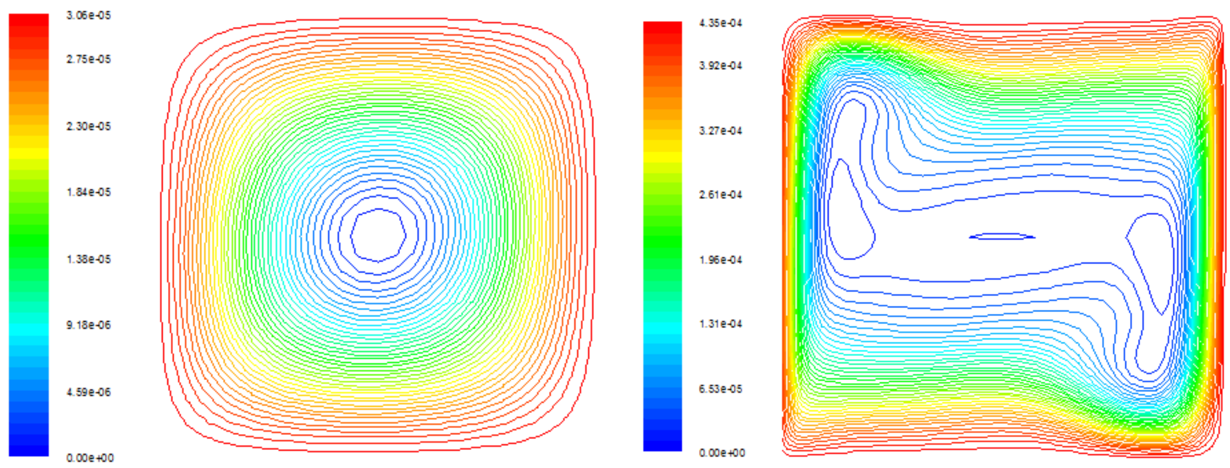
(a) **(b)**

Fig. 4: the velocity vectors for different Rayleigh numbers: a) Ra = 10^3 and b) Ra = 10^6

Figures 4 (a and b) show the air velocity vectors respectively for a Rayleigh number equal to 10^3 and 10^6. It is noted that the velocity is low just near the walls, the liquid jet rises and is parallel to the vertical hot wall with a high velocity. As the liquid jet approaches the upper horizontal wall, it begins to slow down and turns away from the warm wall well below reaching the corner. In this process, changing the direction of flow reduces its velocity and attenuates the convection heat transfer near the corner. Then, the colder liquid jet descends with a slow velocity parallel to the cold vertical wall and the lower horizontal wall. The heating / cooling cycle continues in this way permanently. It should also be noted that the increase in Rayleigh number has a significant effect on the dynamic behavior and the acceleration of the flow inside of the cavity.

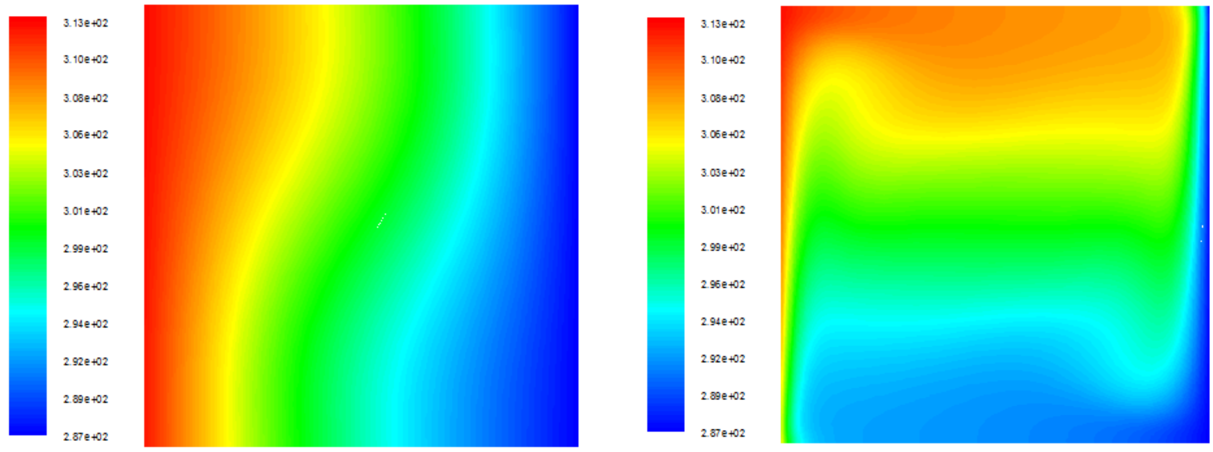
6.3.Thermo-convective structure

Figures 5 and 6 (a and b) respectively show the streamlines and the isothermal lines for two Rayleigh numbers Ra = 10^3 and Ra = 10^6



(a) **(b)**

Fig. 5: the streamlines for the different Rayleigh numbers: a) Ra = 10^3 and b) Ra = 10^6



(a) **(b)**

Fig. 6: The isothermal lines for different Rayleigh numbers: a) Ra = 10^3 and b) Ra = 10^6

It is clear that each of the two configurations contains a simple rotating vortex which takes the form of the cavity, Figure 5 (a and b). Looking at the gradient sign for the current function, we can see that the vortices are turning clockwise. The vortex moves the warm fluid from the left wall along the top of the cavity. As the gravitational force increases, so the buoyancy flow conducted inside the cavities becomes vigorous.

In the air temperature fields for different Rayleigh number Ra = 10^3 and Ra = 10^6, Figure 6 (a and b). We notice that the isotherms become curved (convective regime) more and more with the increase of this number of Rayleigh. The highest temperatures are in the upper half of each cavity. The isotherms are very close to the typical distribution of temperature which corresponds to the limit of pure conduction (parallel to the gravitational field) for a Rayleigh Ra = 10^3 and the isotherms become curved (convective regime) with increasing this number of Rayleigh.

Heat flow values, the Nusselt numbers, for different temperature gradients applied to the active walls in aspect ratio cavities equal to one were also calculated and presented in Table 1.

Table 1: Nusselt and average heat flux for different temperaturegradients and Rayleigh numbers

ΔT [°C]	Q [W/m^2]	Nu	Ra
26	5.98	8,84	9.85. 10^5
46	12.39	10,36	17.43. 10^5
66	19.63	11,44	25.02. 10^5
86	27.50	12,29	32.59. 10^5
106	35.88	13,02	40.17. 10^5
126	44.70	13,64	47.76. 10^5

Table 1 confirms the proportionality between the heat flux exchanged with the active walls, the average Nusselt number with the different temperature gradients and the Rayleigh numbers.

7. Conclusion

Nnumerical study of natural convection in an enclosure subjected to a horizontal gradient of temperature was conducted using the fluent calculation code, which is based on the finite volume method. A first validation work was done comparing our results with those of other authors, the results obtained are in good agreement with the results of El Hassan Ridouane and Antonio Campo [14].

The results obtained show that the Rayleigh number has a significant impact on the behavior of the fluid. This result is well shown in the temperature field contoursof streamlinesand velocity. The average Nusselt number, the average heat flux also recorded an increase with increasing temperature gradient and Rayleigh number.

REFERENCES

[1] N.C. Markato, K.A. Pericleous, Laminar and turbulent natural convection in anenclosed cavity, Int. J. Heat Mass Transf. Vol. 27 (1984) pp.755–772

[2] G. de Vahl Davis, Natural convection of air in a square cavity: a benchmark numerical solution, Int. J. Numer. Methods Fluids Vol.3 (1983) pp.249–264

[3] M.A.R. Sharif, T.R. Mohammad, Natural convection in cavities with constantflux heating at the bottom wall and isothermal cooling from the sidewalls, Int.J. Therm. Sci. Vol.44 (2005) pp.865–878

[4] I.E. Sarris, I. Lekakis, N.S. Vlachos, Natural convection in a 2d enclosure withsinusoidal upper walltemperature, Numer. Heat Transfer, Part A . Vol.42 (2002)pp.513–530

[5] J.M. Hyun, J.W. Lee, Numerical solutions for transient natural convection in asquare cavity with different sidewall temperatures, Int. J. Heat Fluid Flow Vol.10N°2 (1989) pp.146–151

[6] A. Bhattacharya, R.L. Mahajan, Metal foam and finned metal foam heat sinksfor electronics cooling in buoyancy-induced convection, J. Electron. Packag.Vol.128 N°3 (2006) pp.259–266

[7] M. Moawed, Experimental investigation of natural convection from verticaland horizontal helicoidal pipes in HVAC applications, Energy Convers. Manage.Vol.46 N°18 (2005) pp.2996–3013

[8] A.C. Megri, F. Haghighat, Zonal modeling for simulating indoor environment ofbuildings: review, recent developments, and applications, HVAC&R Res. Vol. 13 N°6(2007) pp.887–905

[9] M. Keyhani, T. Dalton, Natural convection heat transfer in horizontal rodbundleenclosures, J. Heat Transf. Vol. 118 N°3 (1996) pp.598–605

[10] S. Narasimhan, J. Majdalani, Characterization of compact heat sink models innatural convection, IEEE Trans. Compon. Packag. Technol. Vol. 25 N°1 (2002) pp.78–86

[11] R.E. Canaan, D.E. Klein, An experimental investigation of natural convectionheat transfer within horizontal spent-fuel assemblies, Nucl. Technol. Vol.116 N°3(1996) pp.306–318

[12] Patankar S V, (1980) Numerical Heat Transfer and Fluid Flow, Hemisphere, New York

[13] Patankar S V, Spalding, D B, A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows, International Journal of Heat and Mass Transfer. Vol.15 (1972) pp.1787-1806

[14] El Hassan Ridouane and Antonio Campo,Free convection performance of circular cavities having two active curved vertical sides and two inactive curved horizontal sides Applied Thermal Engineering.Vol.26 (2006) pp.2409–2416