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Research Article

RAYLEIGH-BENARD CONVECTION STUDY IN A CAVITY FOR A SHEAR THINNING FLUID

B. Ali Benyahia*, N. Ait Messouadene

Laboratoire des Applications Energétiques de l'Hydrogène (LApEH), University of Blida 1, P O Box 270. Blida, Algeria

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ABSTRACT

Rayleigh-Bénard's convection is a classic problem of heat transfer. Since the 1900s, studies for Newtonian fluids have been widely developed in this field and phenomena well understood. On the other hand, the complexity of non-Newtonian behavior makes the number of studies much lower. Among the non-Newtonian behavior, the shear-thinning fluid studies are even rarer. This work focuses on a numerical study of natural convection for a non-Newtonian fluid shear thinning, in the Rayleigh-Bénard configuration. The Carreau-Yasuda model describes the shear thinning behavior. The convective flow considered is confined in a cavity, which is subjected to a vertical temperature gradient, heated from below and cooled from above. The transport equations are discretized by the finite volume method and are solved numerically using a CFD code: "Ansys Fluent".The influence of the control parameters on the flow and heat transfer such as the Rayleigh Ra number, the aspect ratio, A, the Prandtl numbers, Pr, the power index n and the time constant E, are studied.

Keywords: Rayleigh Benard; Shear Thinning Fluid; ANSYS Fluent; lineair stability.

Author Correspondence, e-mail: alibenyahia_brahim@yahoo.com
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1. INTRODUCTION

Rayleigh-Bénard type convection basically refers to the convection between two parallel plates, the bottom plate is heated and the upper plate is cooled. It is a convection induced by the impulse of Archimedes, which opposes two effects exerted on the particles of fluid: the effects of dissipation viscous and thermal, which slow the movement. The control parameter that governs the system is the Rayleigh number. Since the 1900s, numerous studies on Rayleigh Benard's instability have been carried out on Newtonian fluids [1]. The critical value of the Rayleigh number in this case is about 1708. This value was obtained theoretically via a linear stability analysis, and verified experimentally by several studies, for example, in the work of Koschmieder [2], different Newtonian fluids are used in various devices, and the critical value of Ra is found around 1708. Most real and industrial fluids are not Newtonian, that is, their viscosity varies with the shear rate. The importance and the need to study Rayleigh Bernard's convection are obvious. There are several classes of non-Newtonian behavior, such as shear thinning fluid, characterized by a decrease in viscosity as the shear stress increases. The interest in understanding and mastering the rheological behavior of fluids, in convective flows, is essential to provide solutions to the problems encountered in the various branches of activity such as: industrial processes, chemical, petrochemical, pharmaceutical products and particularly in the food industry. Tien and al [3] used the solutions of Carboxyl Methyl Cellulose (CMC) and polyacrylate (Carbopol solutions) with the model of the power law to determine the influence of shear thinning fluid on heat transfer. Liang and Acrivos [4] carried out their experiments with polyacrylamide solutions (Separan AP30) modeled by the Carreau model. It has been observed that shear-thinning fluid tends to favor the transfer of heat in the convective regime. A numerical solution made it possible to highlight the dependence of the fields of function of current, temperature and concentration of the behavior index of the non-Newtonian fluid. Benouared and al [5] have studies numerically the natural convection of non-Newtonian fluids in the configuration of Rayleigh-Bénard (RB). The non-Newtonian fluid rheological behavior was modeled using the Carreau-Yasuda model. The convective flow has been confined in a cavity of finite/infinite aspect ratio, which was subject to a vertical temperature gradient [10-12]. Aspect ratio effects in Rayleigh-Bénard convection of Herschel-Bulkley fluids, studied by Mohammad Saeid Aghighi [15-17]. The objective of this study is the effect of viscous dissipation, which is being taken into consideration while the axial conduction of heat in the fluid is considered negligible. The objective of our work is to study numerically the natural convection for a shear thinning fluid, in the Rayleigh-Bénard configuration.

2. MATHEMATICAL FORMULATION

We are interested in thermal convection in a cavity of h height, with adiabatic vertical walls and horizontal walls subject to constant temperatures respectively T_c and T_f (figure 1). Approximation of Boussinesq, it is given by the following relation:

$$\rho = \rho_0[1 - \beta(T - T_0)] \qquad \text{whith} \qquad \beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \qquad 1$$

Where ρ_0 and T_0 respectively denote the density and the reference temperature and β is the thermal expansion coefficient.

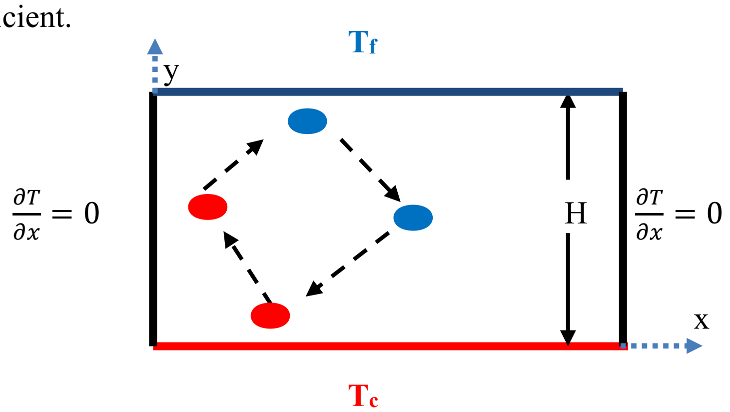


Fig.1. Schematic representation of the flow configuration

The mathematical formulation of convection phenomena is based on the equations linking the different parameters namely: speed, pressure and temperature. These equations come from the averaging of the Navier Stokes equations over time. It is more convenient to present the equations governing the problem in dimensionless form. Numbers without characteristic dimensions will appear and that will considerably reduce the complexity of the problem are given by:

$$X = \frac{x}{H}\,,\; Y = \frac{y}{H}\,, U = \frac{u}{\left(\frac{\alpha}{H}\right)}\,, V = \frac{v}{\left(\frac{\alpha}{H}\right)} P = \frac{p}{\left(\frac{\rho\alpha^2}{H^2}\right)}\,,\; \theta = \frac{T - T_f}{T_c - T_f}\,,\; t = \frac{t\alpha}{H^2}\,,\; \eta = \frac{\mu}{\mu_0} \qquad 2$$

Then with the introduction of the dimensionless variables, the system of equations defines previously takes the following form:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \qquad 3$$

$$\left(\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}\right)= \ -\frac{\partial P}{\partial X}+Pr\left(\frac{\partial \tau_{xx}}{\partial X}+\frac{\partial \tau_{xy}}{\partial Y}\right) \qquad 4$$

$$\left(\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}\right)=-\frac{\partial P}{\partial X}+Pr\left(\frac{\partial \tau_{xy}}{\partial X}+\frac{\partial \tau_{yy}}{\partial Y}\right)+PrRa\theta \qquad 5$$

$$\tau_{xx}=2\eta\frac{\partial U}{\partial X} \qquad \tau_{xy}=\tau_{yx}=\eta\left(\frac{\partial U}{\partial Y}+\frac{\partial V}{\partial X}\right) \qquad \tau_{yy}=2\eta\frac{\partial V}{\partial Y} \qquad 6$$

$$\frac{\partial \theta}{\partial t}+U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2} \qquad 7$$

The parameters Pr and Ra appearing in Eq (5) are the Prandtl and the Rayleigh numbers, respectively, defined as: $Ra=\frac{g\beta H^3}{\alpha v}\left(T_c-T_f\right)$ $\quad$ Pr=γ/α $\quad$ 8

Where α and μ_0 are the fluid thermal diffusivity and dynamic zero-shear rate viscosity, respectively. In non-dimensional form, the apparent viscosity μ in the Carreau-Yasuda model (Bird et al) reduces to: $\mu=\mu_\infty+(\mu_0-\mu_\infty)[1+(E\,\dot{\gamma})^{\,a}]^{\frac{n-1}{a}}$ $\quad$ 9

Where s= μ_0/μ_∞ is the infinite- to zero-shear-rate viscosities ratio. The Carreau-Yasuda model is best suited to represent the rheological behaviour of a wide variety of polymer solutions. The power-law index, n, characterizes the fluid behaviour and E is a dimensionless characteristic time of the fluid. Generally, boundary conditions to solve the equations are as follows: No slip bounder conditions are assumed at the solid wall for velocity. The stress components at the wall are obtained by solving constitutive equations and b applying known velocity boundary conditions. At the outlet, the Neumann boundary conditions are imposed for the flow variables.

$$x=0,\ \ 0<y<H,\ \ \frac{\partial T}{\partial x}=0 \quad ; \qquad 0<x<L,\ \ y=H \qquad T(x,L,t)=T_f \qquad 10$$

$$0<x<L,\ \ y=0,\ \ T(x,L,t)=T_c\ ; \qquad x=L,\ \ 0<y<H,\ \ \frac{\partial T}{\partial x}=0 \qquad 11$$

3. NUMERICAL METHOD

Fluid flows, whether in a laminar or turbulent regime, are described by the system of partial differential equations. Thus, all physical phenomena are governed by this system formed by the equations of continuity, momentum and energy that must be solved to know the characteristics of the thermal field and the flow field. Unfortunately, it is practically impossible to find an analytical and exact solution for such systems because the equations mentioned above are very complex, that is to say non-linear on the one hand and coupled on the other hand. In this case, the use of digital resolution is necessary and prompts us to choose the appropriate numerical method to obtain the best approximations. For this reason, we use numerical methods or software, among this software the Fluent. ANSYS Fluent is the computational fluid dynamics (CFD) software tool allowing going further and faster whiling optimizing product performance. This software includes well-validated physical modeling capabilities to provide fast and precise results on the widest range of CFD applications.The ANSYS Fluent software contains the vast physical modeling capacities necessary to model the dynamics of fluids, heat transfer for both Newtonian and non-Newtonian fluids. The commercial computational fluid dynamics code FLUENT was used to solve the governing equations.

4 RESULTS AND DISCUSSION

In this work, we will present the results followed by a discussion of the effects of the rheological parameters of the Carreau model on flow structure, heat transfer and the existence of subcritical convection. Effects of control parameters on flow and heat transfer will also be examined; namely the aspect ratio, A, the Prandtl number, Pr, and Rayleigh numbers, Ra, the power index n and the time constant E.

4-1 Validation of the numerical code

The numerical code developed to solve the conservation equations was validated in the Newtonian and non-Newtonian case by comparing the results of the present study to those reported by Benouared and al [5]. Validation of the numerical code in terms of mean Nusselt number, Nu_m in the case of a Newtonian fluid in a square cavity filled with air (Table 1).

Table 1: Nusselt number in the case of a square cavity filled with air $A = 1,\ Pr = 0.71$

Ra	10^2	1.5×10^4	10^5	10^6
Reference [5]	2.163	2.42	3.934	6.379
Present study	2.163	2.424	3.925	6.274

Validation of the numerical code in terms of mean Nusselt number, Nu_m in the case of a Non-Newtonian fluid in a cavity filled with water (Table 2, 3). Tables (1) (2) (3) show that with a mesh of 81 × 81 for A = 1, and 161 × 81 for A = 10, good agreement of the results is observed for the average Nusselt values, Nu_m, with a relative error less than 1%.

Table 2: Average Nusselt number Nu_m, in the case of a square A = 1, Pr = 10

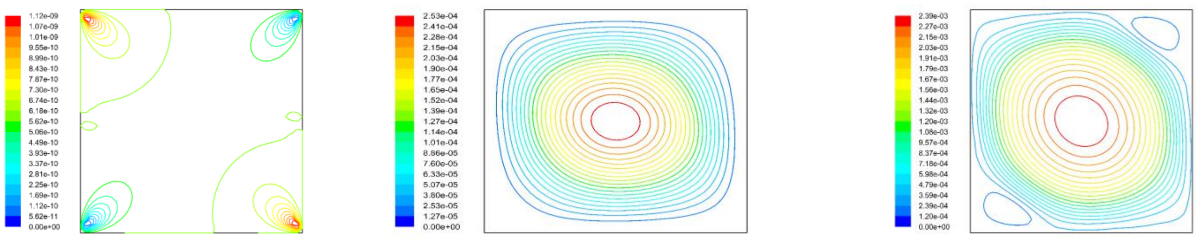
	n = 1		n = 0.8		n = 0.6		n = 0.4	
Ra	Ref [5]	Present study	Ref [5]	Present study	Ref [5]	Present study	Ref [5]	Present study
2000	1.1	1.093	1.4	1.303	2	1.716	2.4	2.285
4000	1.5	1.518	2	1.803	2.4	2.201	2.9	2.768
6000	1.8	1.835	2.2	2.142	2.7	2.567	3.4	3.232
8000	2	2.044	2.4	2.371	2.9	2.836	3.6	3.658
10000	2.1	2.196	2.6	2.544	3.1	3.056	3.9	4.051

Table 3: Validation of the numerical code in terms of average Nusselt number, Nu_m

A = 10, Pr = 10	Ref [5]		Present study	
Ra	n = 1	n = 0.6	n = 1	n = 0.6
2000	1.2	2.7	1.199	2.402
3000	1.6	3.2	1.642	3.283
4000	1.9	3.6	1.897	3.785
5000	2.1	4.1	2.078	4.157
10000	2.6	5.2	2.584	5.168

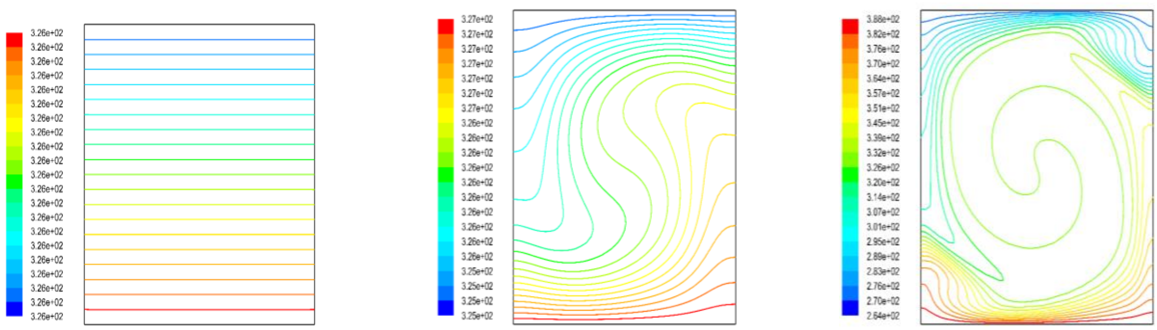
4-2 Newtonian Fluid Case

In this part, the study is based on the effect of increasing the number of Rayleighs on the flow structure and heat transfer of a flow for a Newtonian fluid in a cavity. The variation in Rayleigh number is performed in the range of 5 * 10^2 to 10^4. Figure 2 shows the current lines for different values of Rayleigh number Ra. We remark a flow of particles of the fluid that heats up along the hot wall under the effect of buoyancy and the downward movement of the particles of the fluid that cools along the cold wall under the effect of gravity. For Ra = 10^3, the values of the current function are very small. When the Rayleigh number is increased to Ra =1.7 × 10^3, the flow structure and the values of the current function increase substantially, reflecting a nascent natural convection. For the higher values of Rayleigh number Ra = 10^4, the values of the Current Function corresponding to these values increase significantly, all this leads us to say that natural convection has become preponderant. The current lines are very tight near the active walls. This is explained by the increase in the number of Rayleigh, which leads to a dominance of natural convection at the corners of the cavity.



$Ra = 10^3$ $Ra = 1.5 \times 10^4$ $Ra = 10^6$

Fig.2. Effet of Rayleigh number Ra effect on speed contours for $A = 1, \mathrm{Pr} = 0.71$

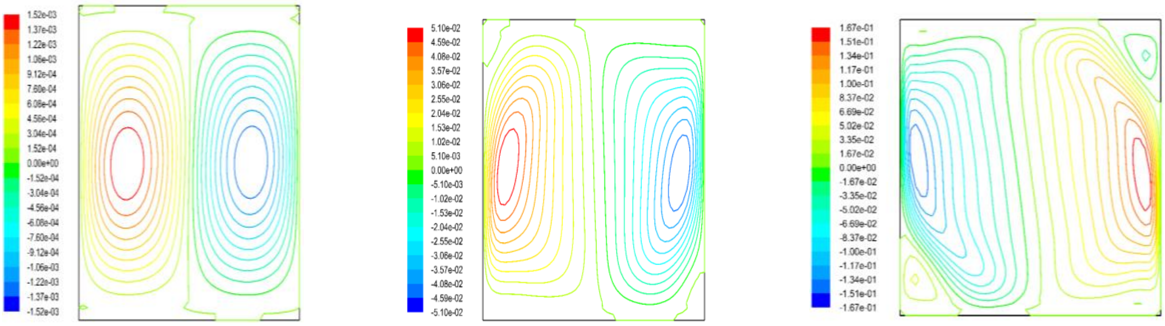


$Ra = 10^3$ $Ra = 1.5 \times 10^4$ $Ra = 10^6$

Fig.3. Effet of Rayleigh number Ra effect on isotherms for $\mathbf{A = 1}$, $\mathbf{Pr = 0.71}$.

Figure 3, represents the thermal field for different numbers of Rayleigh Ra, for Ra =10^3, we remark that the isothermal lines are parallel to the horizontal walls of the cavity, in this case the temperature distribution is simply decreasing from the hot wall to the cold wall. The thermal transfer takes place essentially by conduction, and for Ra $=1.7 \times 10^3$, show that the isothermal lines are slightly deformed according to the direction of rotation of the current lines but remain almost parallel to the cold high wall. Heat transfers always remain dominated by a pseudo-conductive regime. For higher values of the number of Rayleigh Ra $= 10^4$, the corresponding contours show that the isothermal lines deform a lot to become parallel to the inactive vertical walls in the middle of the enclosure and follow the shape of the horizontal active walls while remaining very tight which shows a very intense transfer in these regions. The increase in the number of Rayleigh therefore reflects an intensification of natural convection. The increase in the number of Rayleigh therefore reflects an intensification of natural convection. Shows a high intense transfert in these regions. The increase in the Rayleigh number therefore reflects an intensification of natural convection. Figure (4) shows the contours of the velocity v for different values of the Rayleigh number Ra, shows a profile symmetrical with respect to the centre of the cavity and we remark an increase in the velocity gradient near the vertical adiabatic walls, with the increase in the number of Rayleigh Ra. Figures (5), (6), illustrate the velocity profiles; longitudinal and transverse as a function of x, for different values of Rayleigh number Ra. The velocity profile u (Figure 5) shows that it is symmetrical with respect to the centre of the cavity. For small values of Rayleigh number Ra $= 10^4$, the velocity is almost zero. With the increase in the number of Rayleigh, we observe the appearance of the maximum and minimum values of the speed u near the horizontal active walls. For the velocity v, (Figure 6) also shows a symmetrical profile with consideration to the centre of the cavity and one notices an increase of the gradient of the velocity near the vertical adiabatic walls, with the increase of the number of Rayleigh. We can conclude that the increase in the number of Rayleigh results in a gradual increase of speeds.

Figure 7 represents the variation of the local Nusselt number as a function of X for different values of the Rayleigh Ra number, it is noted that the number of local Nusselt Nu increases with increasing Rayleigh number and this means that the heat exchange is best for high Rayleigh numbers.



$\mathrm{Ra} = 1.7 \times 10^4$ $\mathrm{Ra} = 10^5$ $\mathrm{Ra} = 10^6$

Fig.4. Effet of Rayleigh number Ra effect on speed contours $A = 1$, $\mathrm{Pr} = 0.71$

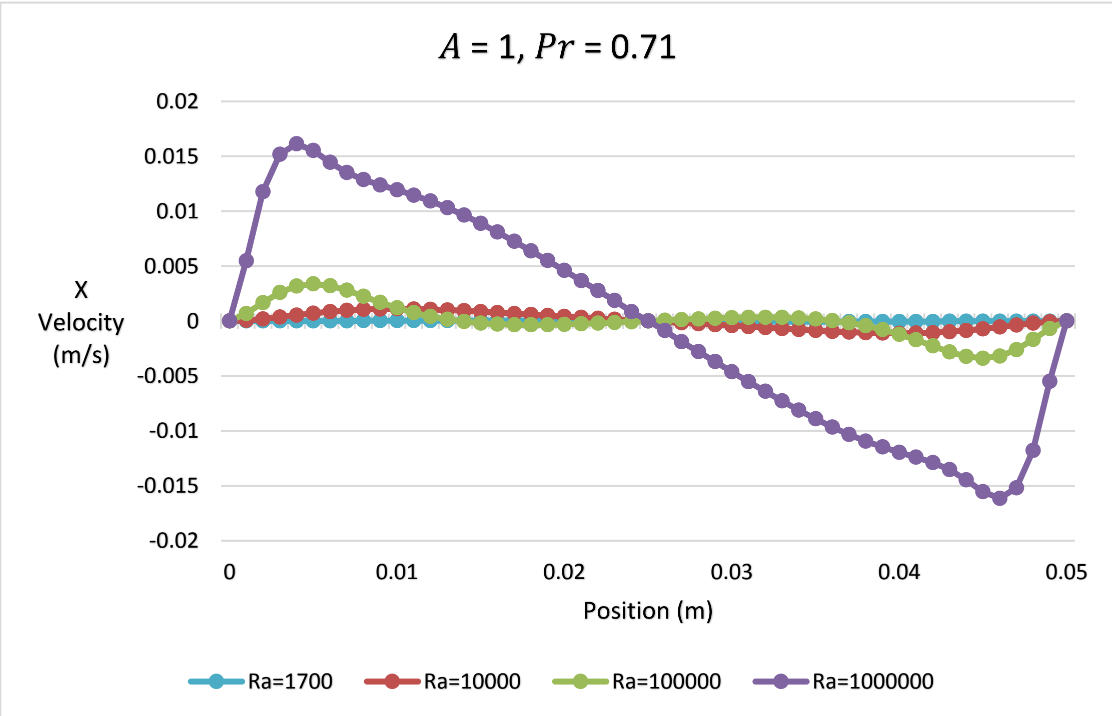


Fig.5. Effect of Rayleigh Number Ra on the variation of velocities "u" as a function of X

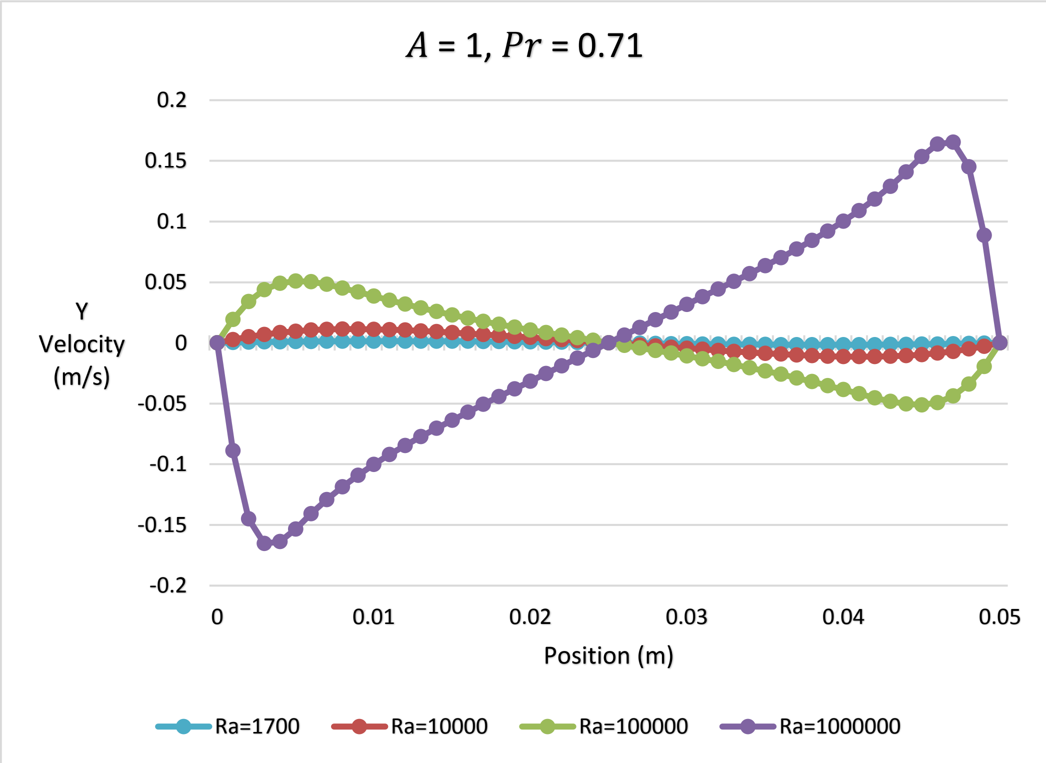


Fig.6. Effect of Rayleigh Ra number on speed "v" according to X

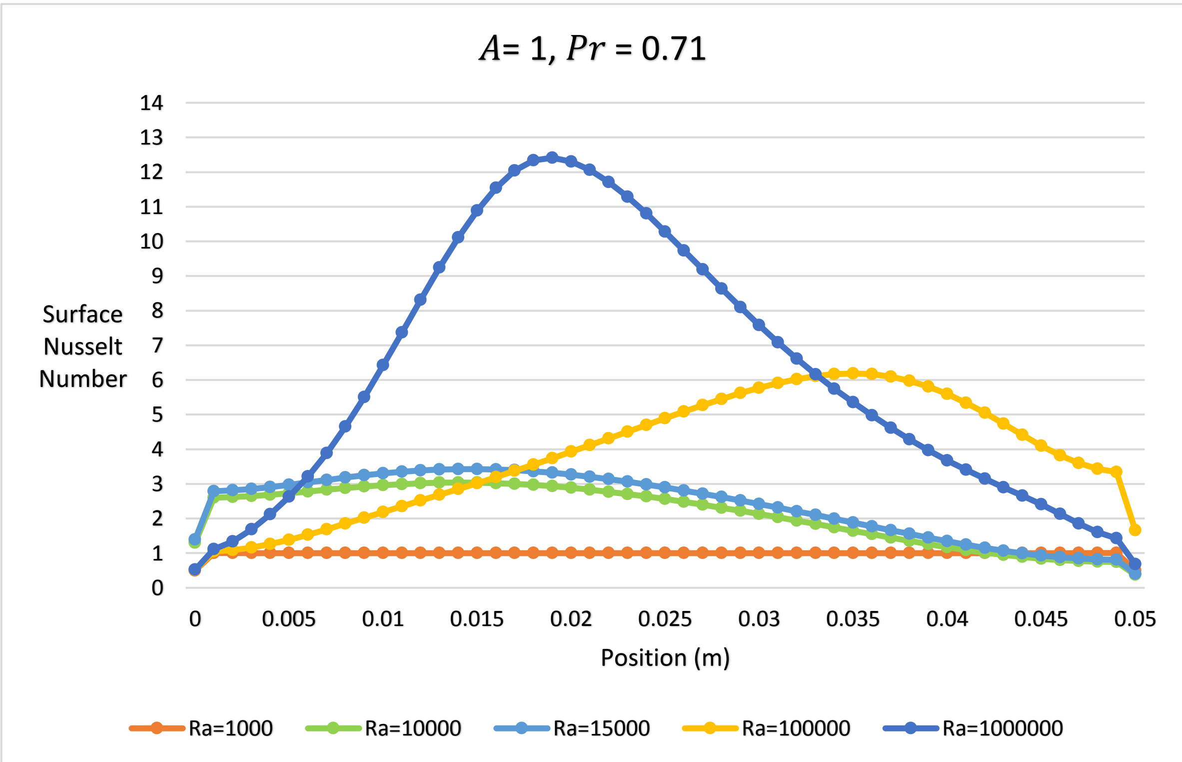
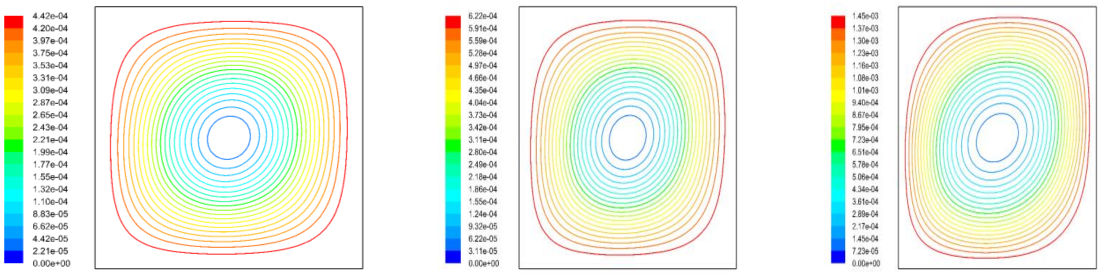


Fig.7. Effect of Ra on the variation of the local Nusselt number according to X

4-3 Non - Newtonian Fluid Case

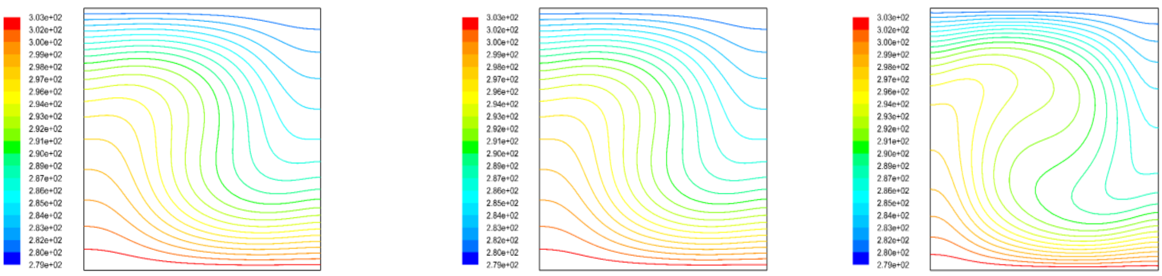
In this part of a non-Newtonian model Carreau-Yasuda fluid, the study based on the effect of variation of the power index "n" on the structure and the heat transfer of a non-Newtonian fluid by natural convection in the same previous cavity. Results with the works of Benouared et al [5], we found a good agreement table (2), (3). Figure (8), (9) shows the current and isothermal lines when Ra = 4000 for defferent values of the fluid index n. Disturbance and convection are observed to increase in the case of a shear thinning fluid compared to the Newtonian case (n = 1). The results show that the heat transfer and convection force increase with increasing number Ra and decreasing the fluid index n**.**



n=0.8 n=0.6 n=0.4

Fig.8. Effect of the fluid index "n" on the flow field and the isotherm for $\boldsymbol{Ra = 4000,\ E = 0.4,\ s = 0.01. A = 1,\ Pr = 10}$

Figures (10), (11), confirm that when the power index (n) decreases, the intensity of the flow increases in the profile of the horizontal component of the speed (u), and the vertical component of velocity (v).



n=0.8 n= 0.6 n= 0.4

Fig. 9. Effect of the fluid index "n" on the variation of the components "u" as a function of X for $\mathbf{Ra = 4000,\ E = 0.4,\ s = 0.01}$

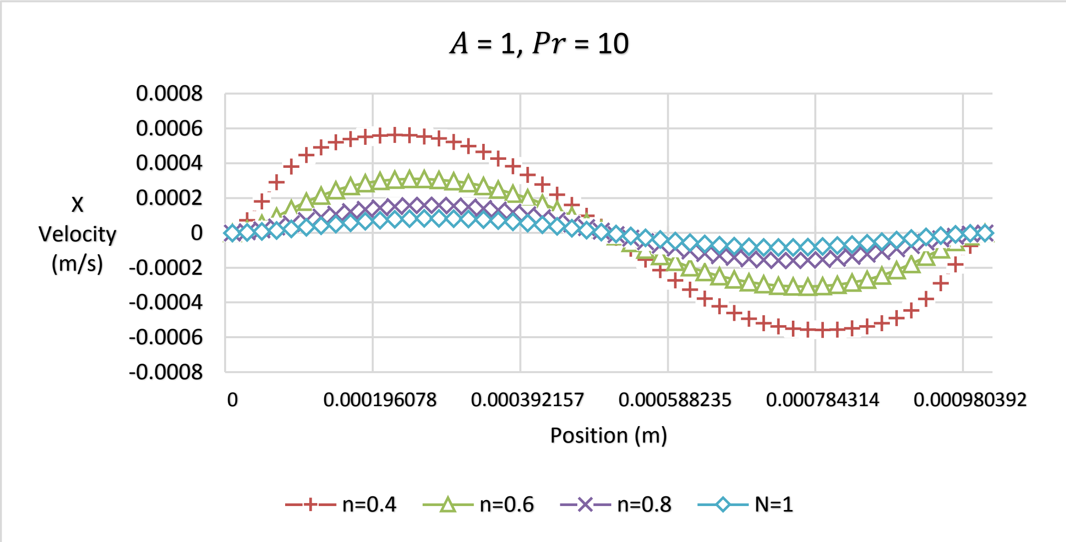


Fig.10. Effect of the fluid index "n" on the variation of the components of the velocity "u" as a function of X for Ra = 4000, E = 0.4, s = 0.01

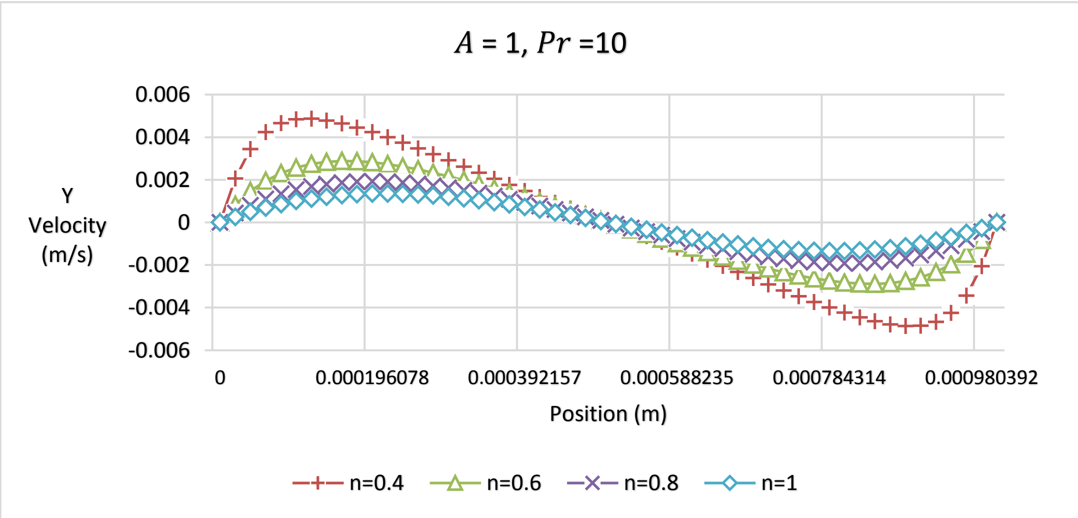


Fig.11. Effect of the fluid index "n" on the variation of the components of the velocity "v" as a function of X for Ra = 4000, E = 0.4, s = 0.01

Figure 12 shows the effect of the power index "n" on the variation of the average Nusselt number Nu_m as a function of different values of the Rayleigh Ra number. The Nusselt number measures the efficiency of the convection, so if $Nu_m = 1$ the heat transfer is by conduction, for the fluid index "n" for the non-Newtonian fluid we note that the decrease of the index causes a strong convection with Rayleigh number increase, its means that the mean Nusselt number increases with increasing Rayleigh number and decreasing the fluid index "n".

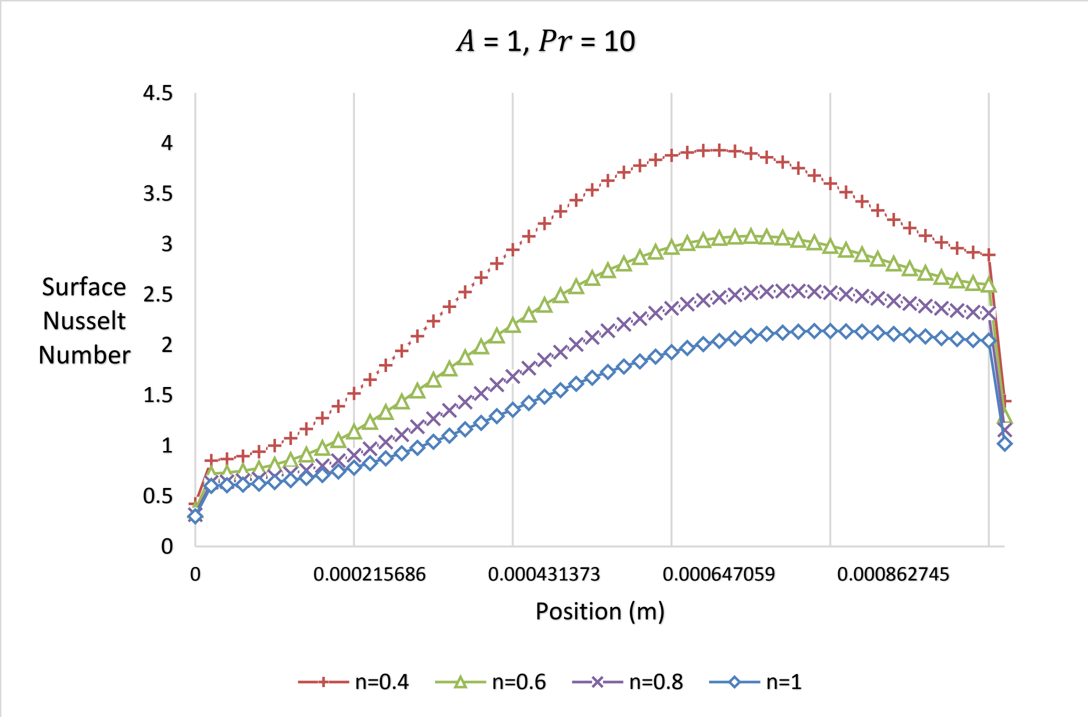


Fig.12. Effect of the fluid index "n" on the local Nusselt number Nu as a function of X for $\boldsymbol{Ra = 4000,\ E = 0.4,\ s = 0.01}$

Figure 13 shows the effect of the index 'n' on the variation of the Nu $_m$ Rayleigh Ra number function. In general, this number increases as "n" decreases. For a given value of "n", the Nusselt number increases as Ra increases.The effect of the Rayleigh number Ra on the average Nusselt number Nu_m for different values of the adimensional time constant "E" for a power index n = 0.4. It can be seen from Figure (14) that for increasing the dimensionless time constant "E" causes a strong convection with increasing Rayleigh Ra number, it means that the average number of Nusselt increases with increasing Rayleigh Ra number. For a value of E = 0 we find the values of mean Nusselt Nu_m, of the Newtonian case (n = 1). The influence of the variation of the form ratio on the flow and the heat transfer, are studied in the following. Thus, in Figures (15) and (16), we represent the temperature fields and the current lines, for different values of the ratio of form A = 1 and A = 10 with the same number of Rayleigh Ra and for Pr = 10, n = 0.6, E = 0.4, s = 0.01.

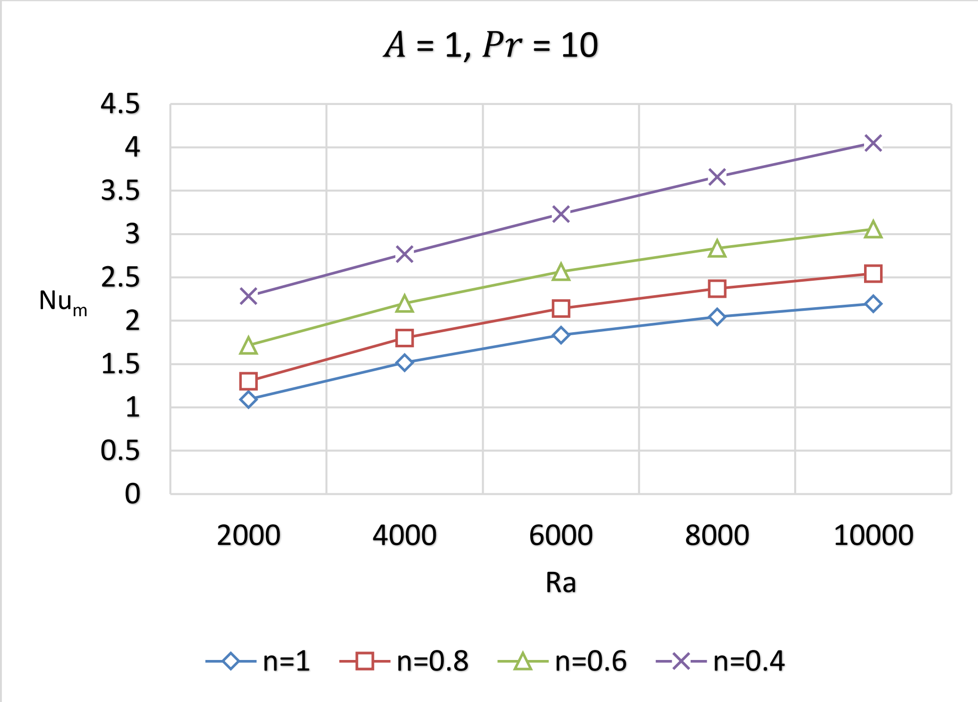


Fig.13. Effect of the index 'n' on the variation of the Nu $_m$ Rayleigh Ra number function

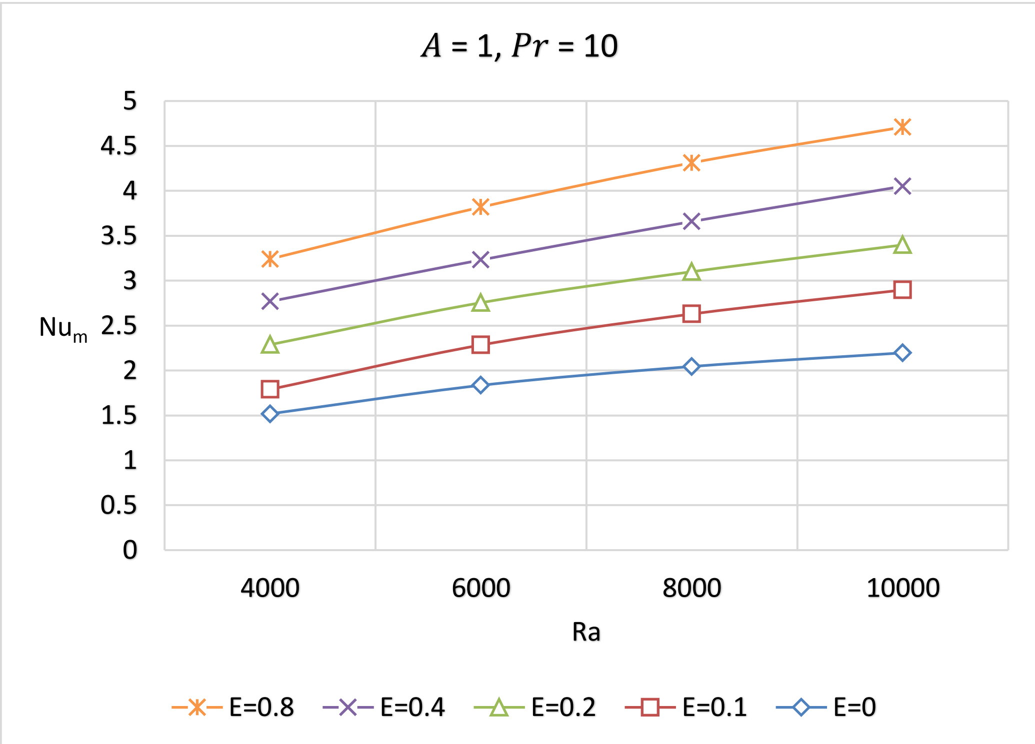
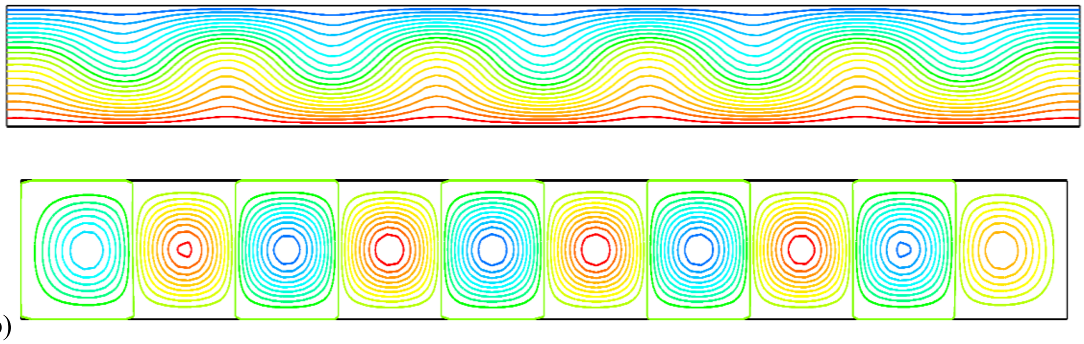
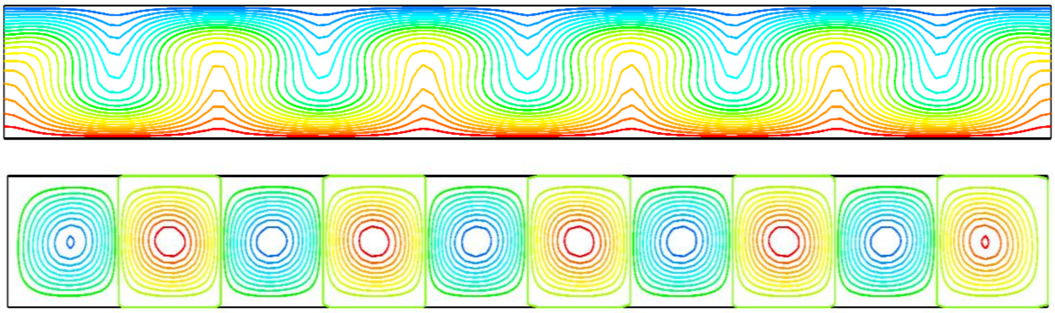


Fig.14. The effect of the Rayleigh number Ra on the mean Nusselt number Nu_m for different values of E with: A = 1, Pr = 10, n = 0.4, s = 0.01



(a) (b)

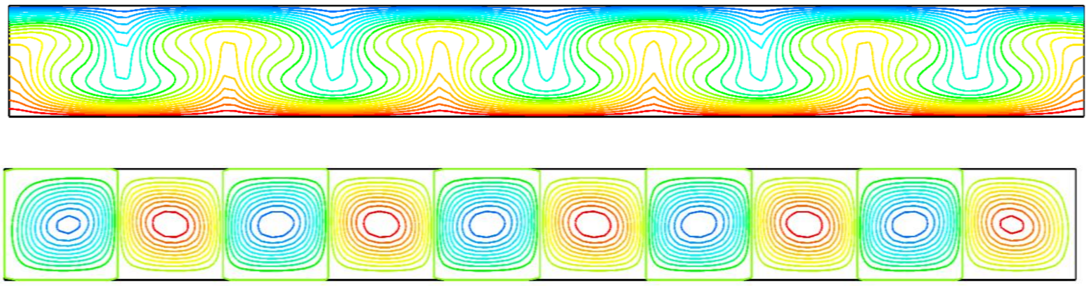
$\boldsymbol{Ra} = \mathbf{2000}$, $\mathbf{A} = \mathbf{10}$



(a) (b)

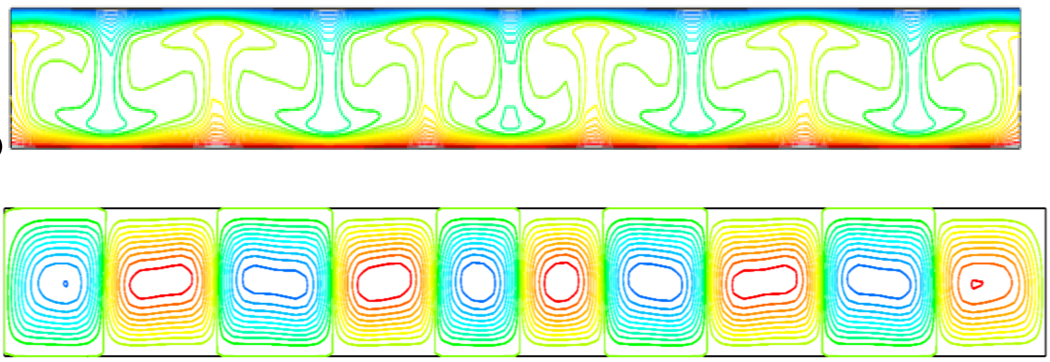
$\boldsymbol{Ra} = \mathbf{4000}$, $\mathbf{A} = \mathbf{10}$

Fig.15. The influence of ratio A on the flow and heat transfer for the number of different values that Rayleigh Ra**,** for $\boldsymbol{Pr} = \mathbf{10}, \boldsymbol{n} = \mathbf{0.6}, \boldsymbol{E} = \mathbf{0.4}, \boldsymbol{s} = \mathbf{0.01}$. (a) Isotherm (b) Speed contours



(a) (b)

$Ra = 2000$, $\mathrm{A} = 10$



(a) (b)

$Ra = 4000$, $\mathrm{A} = 10$

Fig.16. The influence of ratio A on the flow and the heat transfer for different values of Ra, with Pr = 10, n = 0.6, E = 0.4, s = 0.01. Ra = 10^5, A = 10. (a) Isotherm (b) speed contours

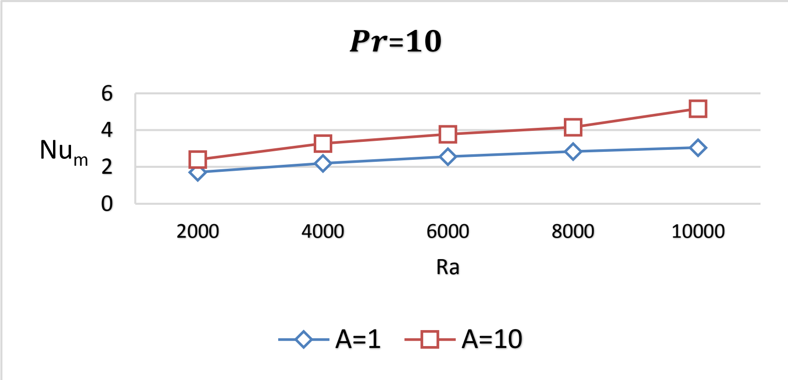


Fig.17. The influence of ratio A on the number of mean Nusselt Nu_m function of Ra, with $n = 0.6,\ E = 0.4,\ s = 0.01$

According to the figures (15) and (16), we note that the increase in the aspect ratio A, an influence on change of number of cells appears. The number of these cells (rolls) equal or aspect ratio of the cavity. From Figure 17, we can see that the mean Nusselt number Nu_m increases with increasing aspect ratios for n = 0.6, E = 0.4, s = 0.01.

6. CONCLUSION

This work relates to a numerical study of natural convection in a cavity filled with a non-Newtonian shear thinning fluid type, described by the Carreau model. The simulation of this problem was performed using an Ansys Fluent business calculation code. Numerical results have led us to clarify the influence of rheological parameters on flux and heat transfer, such as Rayleigh Ra number, length ratio A, Prandtl numbers, Pr, fluid index n and constant of time E, therefore the concentration of the fluid. The main findings deduced from this study. The increase in the number of Rayleigh Ra number has allowed us to observe that the latter has a direct influence on the structure of the flow as well as on the heat transfer. The Nusselt number is sensitive to the fluid index n and the dimensionless time constant E. The average Nusselt number increases with increasing Rayleigh number and decreasing the n power index. Increasing the adimensional time constant E causes a strong convection with increasing Rayleigh Ra number. The average number of nusselt increases with decreases in fluid concentration. The increase of form ratio A, influence on the change of number of cells appear. The number of these cells equals or aspect ratio of the cavity.

7. ABRIVIATIONS

D_{ij} rate of strain tensor [s^{-1}]

g gravitational acceleration [ms^{-2}]

h convection heat transfer coefficient [$Wm^{-2}K^{-1}$]

k Thermal conductivity [$W m^{-1}K^{-1}$]

K consistency coefficient [$Nsnm^{-2}$]

L Cavity length [m]

n power-law index [-]

Nu Nusselt number [-]

Nu_m average Nusselt number [-]

p fluid pressure [Nm^{-2}]

p modified pressure [Nm^{-2}]

P dimensionless pressure[-]

Pr Prandtl number[-]

q’’ heat flux [Wm^{-2}]

Ra Rayleigh number[-]

s heat source distance from the left wall [m]

S dimensionless distance of heat source from the left wall [-]

T temperature [K]

u,v velocity components in x, y directions [ms^{-1}]

U,V Dimensionless velocity components [-]

w Length of the heat source [m]

W Ensionless length of the heat source [-]

x, y Cartesian coordinates [m]

Greek symbols

α thermal diffusivity [m^2s^{-1}]

β Thermal expansion coefficient [K^{-1}]

ΔT Reference temperature difference [K]

τ_{ij} Stress tensor [Nm^{-2}]

θ Dimensionless temperature[-]

μ Dynamic viscosity [Nsm^{-2}]

μ_a* Dimensionless apparent viscosity [-]

ρ Density [$kg\ m^{-3}$]

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