Numerical Study of Heat Transfer by Mixed Convection in a Cavity Filled With Nanofluid: Influence of Reynolds and Grashof Numbers

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Abstract: - In this work, a numerical study of stationary laminar mixed convection in a ventilated square cavity has been presented. The cavity is filled with different nanofluids and contains two gates (ports) to enter and exit the flow. The straight vertical wall is maintained at a warm temperature, while the other walls are considered adiabatic. The equations governing flow and heat transfer have been solved by the finite volume method using a second-order centered Upwind scheme. Numerical simulations are carried out in the case of pure water fluid, and mixtures of this basic fluid and nanoparticles (***Ag*** and ***Cu***), for ***Ri*** varying from (0.04 to 4) and a volume fraction of the nanoparticles between (0% and 10%). The study presented in this work is devoted to a dynamic study in which the Grashof number is fixed at 10^4, and the Reynolds number is varied. The numerical results obtained show that the heat transfer increases with the increase in the volume fraction also that the enhancement of the product of entropy generation and heat transfer increases considerably with the increase in the Reynolds number. The most effective nanoparticles for increasing the heat exchange rate are ***Ag***. The latter is characterized by a large local Nusselt number, that is to say, a very good heat transfer compared to that of metallic ***Cu*** nanoparticles.

Key-Words: - Heat transfer, nanofluid, mixed convection, cavity, Richardson number.

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1 Introduction

One of the new strategies for optimizing heat exchange consists in modifying the nature of the heat transfer fluid to improve its thermal properties. Nanofluids are now considered to be a new category of fluids, making it possible to improve the thermal performance of systems involving convective exchanges, compared to traditional heat transfer fluids (water, ethylene glycol, or propylene glycol), [1]. Nanofluids refer to a liquid in which particles of metals or metal oxides of nano-metric size are suspended, [2]. Recently, a new type of nanofluid has attracted the attention of researchers, they are hybrid nanofluids obtained by dispersing, in a basic fluid, two kinds of nanoparticles, [3].

Many studies have dealt with mixed convection within cavities, given its involvement in various industrial systems and processes, such as solar collectors, cooling of electronic components, and heat exchangers. This takes place when dealing with ventilated cavities and/or those with a wall set in translational motion, [4]. In addition, work on the study of convective phenomena within ventilated cavities has essentially concerned simple and regular geometries (square, rectangular, etc...). On the other hand, few studies have dealt with the case of more complex geometries such as that of Tmartnhad et al, [5]. The latter numerically analyzed the heat transfer, in a trapezoidal cavity ventilated and crossed by air.

In recent years, some authors have highlighted the good thermal performance offered by ventilated cavities through which nanofluids pass. The literature reveals that few works in this area have been developed and that the field remains to be explored. Let us cite, for example, the study undertaken by Soutiji et al, [6]. Whose numerical study focused on the heat transfer within a ventilated square cavity and crossed by a nanofluid (Al_2O_3-water). The latter varied the location of the discharge opening. It appears that the average Nusselt number increases with the increase in the Reynolds and Richardson numbers and the volume fraction. Shahi et al, [7]. Carried out a numerical study concerning the mixed convection within a nanofluid (Cu-Water) in a ventilated square cavity of which a portion of its base is subjected to a flow of heat. Their results indicate the addition of nanoparticles leads to an increase in the average Nusselt number. Recently, Kalidasan et al, [8]. Have considered in their numerical study, the case of a ventilated square cavity with an adiabatic obstacle in its center. The authors were interested in the contribution of the use of a hybrid nanofluid (consisting of nanoparticles of diamond and cobalt oxide in water as a suspending fluid) on the thermal performance of the cavity.

2 Geometry and Simulation Methods

The considered physical system is schematized in (Fig.1). A square cavity filled with nanofluid of side ***H***, with two openings of ***L= H/8***. The right wall relative to the horizontal, along the direction ***X***, is maintained at a hot temperature ***Tc***. and the left one and the other walls are kept adiabatic. The flow through the left opening of the wall has a temperature T_0 and a uniform velocity U_0. The acceleration of gravity acts parallel to the side walls. The entrance is located in the lower left corner, while the exit is located in the lower right corner. Numerical simulations are carried out in the case of pure water fluid, and mixtures of this basic fluid and nanoparticles ***(Ag and Cu)***, for ***Ri*** varying from 0.04 to 4, and a volume fraction of the nanoparticles comprised between (0% and 10%). To deeply examine the effects of relevant parameters on the hydrodynamic flow and heat transfer in our setup.

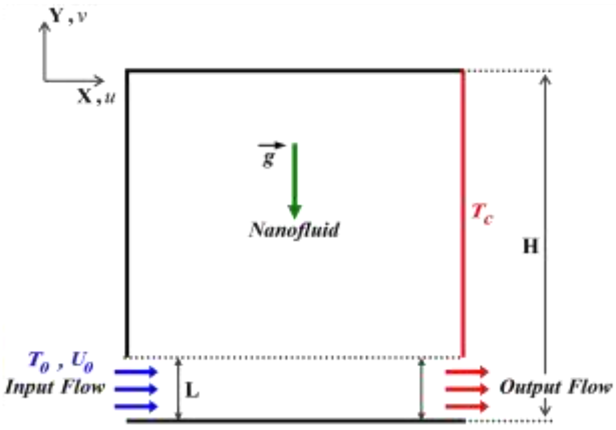


Fig.1, Schematization of the physical problem studied.

3 Mathematical model

3.1 Governing equations

The flow is considered to be two-dimensional, stationary, and laminar, and the physical properties are assumed to be constant. The Boussinesq approximation is validated, it consists in considering that the variations of the density are negligible at the level of all the terms of the momentum equations **(** $\boldsymbol{\rho = \rho_0}$**)**, except at the level of the gravity term. The variation of $\boldsymbol{\rho}$ as a function of temperature is given as follows:

$\rho = \rho_0[1 - \beta(T - T_0)]$.

Viscous dissipation in the energy equation is neglected. Taking into account the assumptions mentioned above, the governing equations can be written in a two-dimensional form as follows:

Continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

Momentum equation, following (x)

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{1}{\rho_{nf}}[-\frac{\partial p}{\partial x} + \mu_{nf}(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}) \quad (2)$$

Momentum equation, following (y)

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = \frac{1}{\rho_{nf}}[-\frac{\partial p}{\partial y} + \mu_{nf}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + (\rho\beta)_{nf} + g(T - T_0) \quad (3)$$

Energy equation

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha_{nf}(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}) \quad (4)$$

With $\alpha_{nf} = \frac{k_{nf}}{(\rho C_p)_{nf}}$

Where the properties of the nanofluid can be defined according to, Brinkman and Maxwell-Garnett:

$$\rho_{nf} = \rho_s\varphi + \rho_f(1-\varphi) \quad (5)$$

$$C_{p_{nf}} = (1-\varphi)C_{p_f} + \varphi C_{p_s} \quad (6)$$

$$\mu_{nf} = \mu_f(1-\varphi)^{-2.5} \quad (7)$$

$$\frac{k_{nf}}{k_f} = \frac{k_s+2k_f-2\varphi(k_f-k_s)}{k_s+2k_f+\varphi(k_f-k_s)} \quad (8)$$

$$\beta_{nf} = \beta_f(1-\varphi) + \beta_f\varphi \quad (9)$$

The mixed convection parameter seen in the above equation, ***Gr/Re^2***, is also called the Richardson number, ***Ri***. Note that the Grashof number is based on the temperature difference of the hot and fluid sidewalls because the type of boundary conditions is considered the heating element at the walls. The dimensionless numbers observed in the above equations, ***Re, Gr***, and ***Pr***, are the Reynolds, Grashof, and Prandtl numbers, respectively. They are defined as follows:

$$\mathrm{Re} = \frac{u_1 H}{\nu},\ Gr = \frac{g\beta\Delta T\, H^3}{\nu^2} \text{ and } \mathrm{Pr} = \frac{\nu}{\alpha} \quad (10)$$

The local Nusselt number along the vertical walls can be expressed by:

$$Nu(y) = -\frac{k_{nf}}{k_f}\left(\frac{\partial T}{\partial x}\right)_{wall} \quad (11)$$

The average Nusselt number is determined by integrating the local Nusselt number along the two vertical walls:

$$\overline{Nu} = \frac{1}{A}\int_A Nu(y)dA \quad (12)$$

The dimensionless parameters in the above equations are defined as follows:

$$X = \frac{x}{H},\quad Y = \frac{y}{H},\quad U = \frac{u}{u_0},\quad V = \frac{v}{u_0},$$

$$P = \frac{p}{\rho u_0^2} \quad ,(13)$$

The boundary conditions of mixed convection are listed in the following table:

Table 1. Hydrodynamic and thermal boundary conditions.

Setting	Hydrodynamic conditions	Thermal conditions
Bottom wall	$u = 0, v = 0$	$\frac{\partial T}{\partial y} = 0$
Upper wall	$u = 0, v = 0$	$\frac{\partial T}{\partial y} = 0$
Straight wall	$u = 0, v = 0$	$T = T_c$
Left wall	$u = 0, v = 0$	$\frac{\partial T}{\partial x} = 0$
Hall	$u = U_0, v = 0$	$T = T_0$
Exit	$\frac{\partial u}{\partial x} = 0, v = 0$	$\frac{\partial T}{\partial x} = 0$

3.2 Numerical Algorithms

The governing coupled equations are transformed into sets of algebraic equations using the finite volume method and are solved by the SIMPLE algorithm. The shifted grid system is used, and the convective terms are handled by the centered second-order upwind scheme. Three different meshes were used, to see their effects on the numerical solution, namely: 80×80, 100×100 and 120×120 control volumes. Due to the computation time and the precision of the results, we chose the 100×100 mesh along the present work. It is thinner near the walls where a significant change in physical variables is expected.

4 Analysis and Interpretation of Results

4.1 Validation

In order to verify the accuracy of the numerical results obtained in this work with the FLUENT code, a validation of our numerical simulation was made by comparing with the numerical studies of Sumon Saha et al, [9]. Who studied a rectangular cavity with adiabatic walls heated at the bottom by an imposed heatflux. Our results are carried out under the same conditions but here we heated the side walls with the Dirichlet condition (fixed imposed temperature). This comparison was carried out under the conditions of ***Pr=0.72***, ***Re=100*** and ***Ri=0.1***. The figures below show the clear presence of cells in the middle of the cavity with an excellent comparison between the current results and the numerical results found in the literature by Sumon Saha et al [9] with a maximum deviation of around 6%.

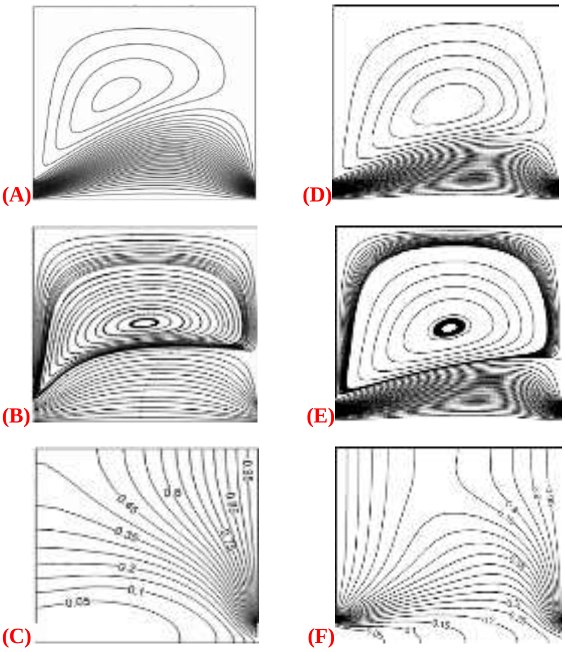


Fig.2, Comparison of isocontours of current functions, for validation. (E, F and F) Present work, (A, B and C) Numerical results from Sumon Saha et al [9].

4.2 Effect of the Richardson number (Ri)

This study predicted the behavior of the flow structure between a multicellular structure dominated by natural convection when the Reynolds number is high, and a multicellular structure dominated by forced convection when the Reynolds number is low.

The streamlines and the isotherms are shown in (fig.3), (fig.4) and (fig.5) respectively for the volume fractions (φ=0, pure water), (φ =0.06 Cu/ Water) and (φ= 0.1 Ag/ Water). The distribution of heat in the cavity is consistent with the circulation of the nanofluid revealed by this current lines illustrated in the figures. Indeed, we observe a heating of the nanofluid throughout the left wall closest to the heating element up to the outlet for all values of the Reynolds number. We note that in the vicinity of the hot wall and the other cold walls, the existence of a crushing of the fluid because of the reduction of the passage section at the entrance of the cavity, we find that the isotherms are almost parallels for low Reynolds values.

The position of the heating element has an influence on the heat transfer, it is noted that the high temperatures are localized in narrow spaces in the vicinity of the hot wall, which correspond to the thickness of the thermal boundary layers, and which are largely influenced by the Reynolds number. Far from the hot wall, the temperature gradients are weak. A different flow structure is observed at each Reynolds number which makes it possible to identify the presence of the main vortex and/or the secondary vortex, for increasingly large numbers. The size of the vortex becomes more and more important (the major upper part of the cavity is occupied by a recirculation zone).

Thus, a significant flow along the bottom wall of the inlet to the outlet extends sometimes when the Reynolds number is low towards the upper part of the cavity. The flow structure (vortex) is monocellular represented by a large cell of elliptical shape; this is explained by the fluid trajectory, for low values of the Reynolds number represented by a rotating vortex call primary vortex in the opposite direction of a needle of a watch. This phenomenon is created by the fact that the fluid next to the hot wall receives heat and becomes lighter (its density decreases) and ascending due to the buoyancy of Archimedes. On the other hand, near the cold wall, it cools and becomes heavier and descending, then while increasing the Reynolds number, the single-cell flow breaks down into two cells and becomes bicellular. Also note, for example, for de Re = 500, an asymmetrical cell is observed. It explains the predominance of natural convection. When the Reynolds number increases, the vortex instability is marked by the flow jet effect, which changes the nature of heat transfer by natural convection to forced convection and the main cell is positioned in the center of the cavity.Note that for all Reynolds numbers, there is no eloquent inequality between the streamlines of pure water and the nanofluid. We can see the impact of the presence of nanoparticles on the streamlines each time the Reynolds number decreases.

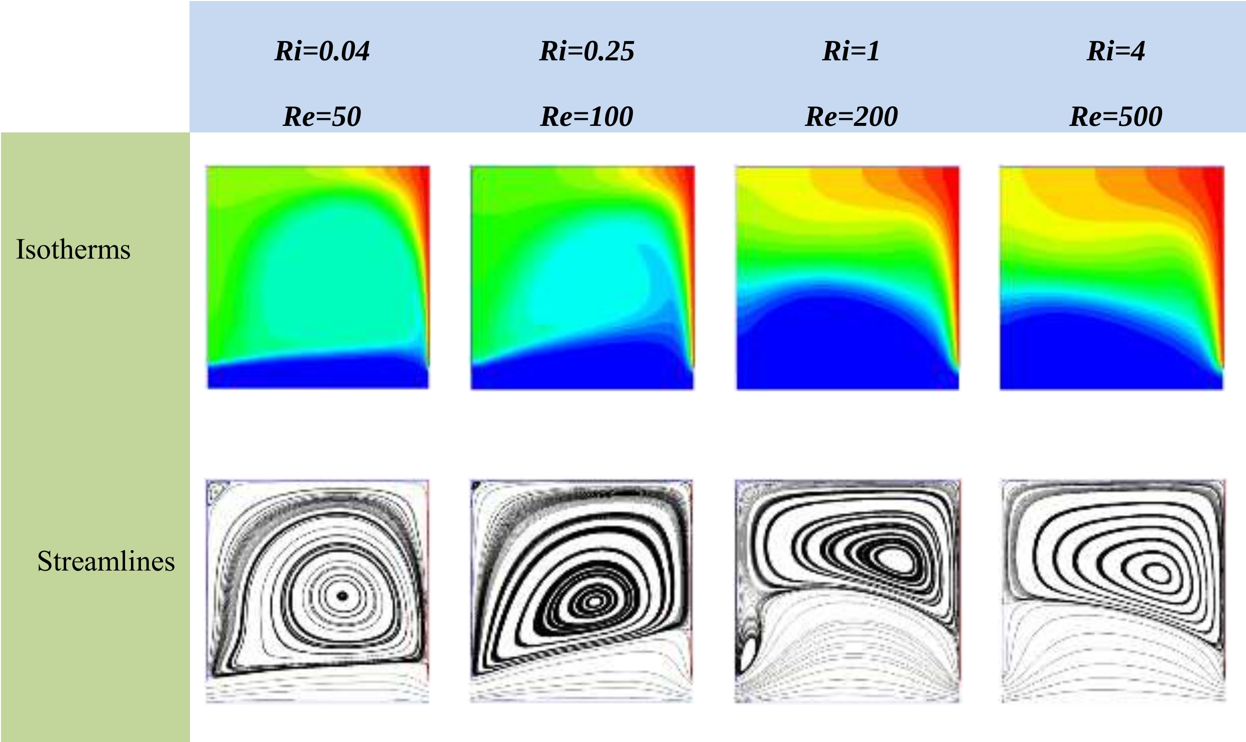


Fig. 3, Contours of isotherms and streamlines in the enclosure (cavity) filled with pure water (φ=0) at different Reynolds numbers, Gr = 10^4.

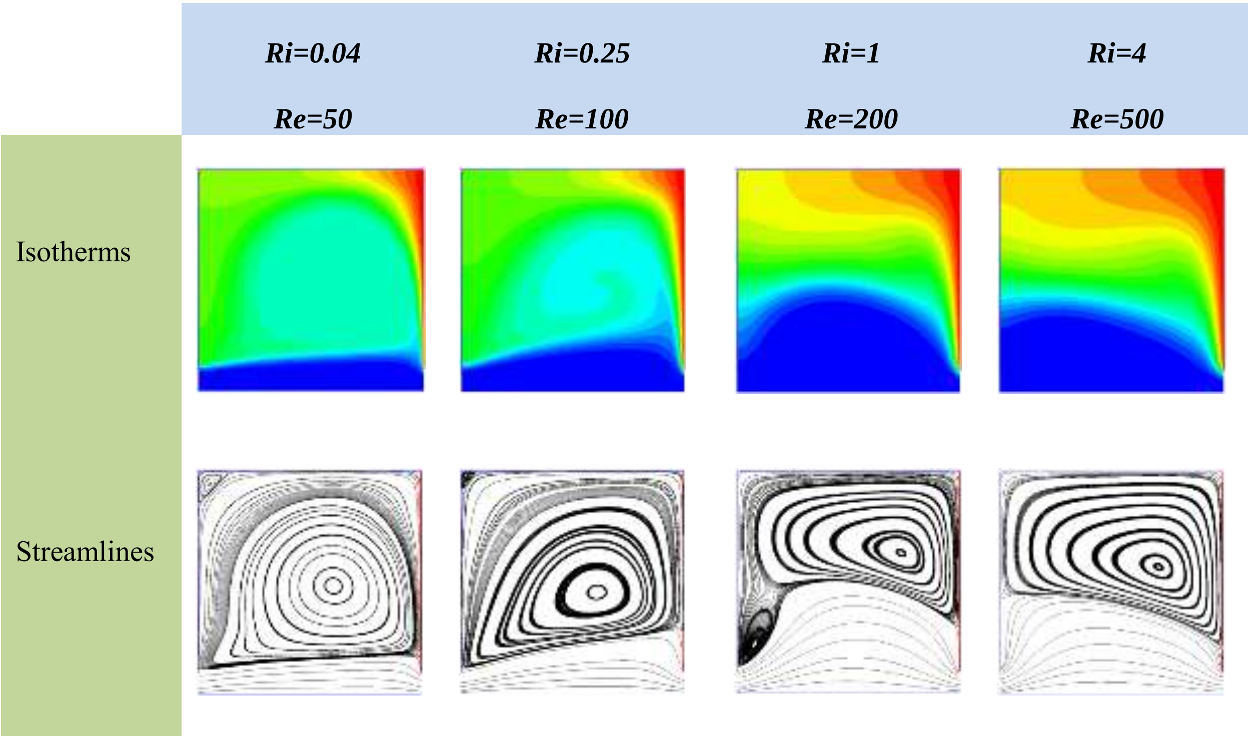


Fig. 4, Contours of isotherms and streamlines in the enclosure (cavity) filled with Nanofluid (Cu/Water, φ=0.06) at different Reynolds numbers, Gr = 10^4.

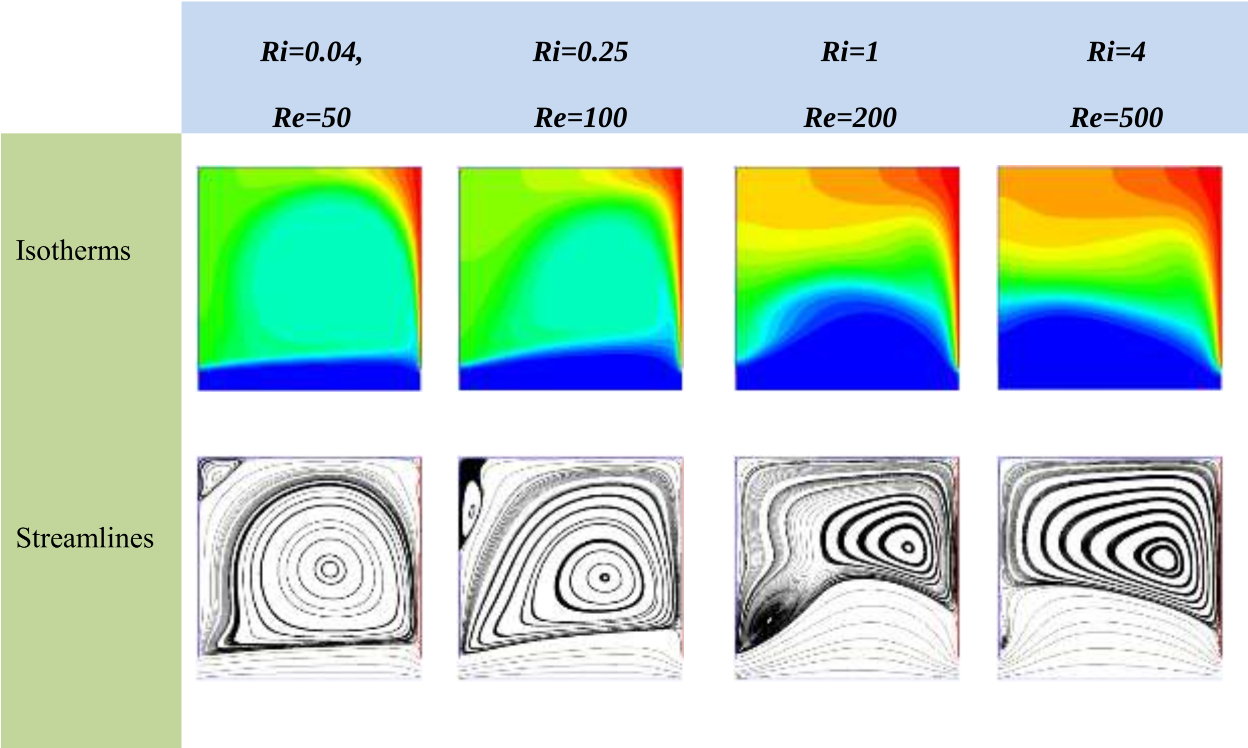


Fig. 5, Contours of isotherms and streamlines in the enclosure (cavity) filled with Nanofluid (Ag/Water, φ=0.1) at different Reynolds numbers, Gr = 10^4.

For low Reynolds numbers, the distribution of isotherms inside the cavity gives a maximum temperature, whereas, for Reynolds numbers greater than 100, the temperature of the nanofluid is the lowest. This behavior can be explained by the higher density and effective dynamic viscosity of nanofluids.

In (fig.6) illustrates the temperature evolution along the Y direction at x = 0.5 H of different Richardson numbers for nanofluids (Cu/Water, φ=0%) and (Cu/Water, φ= 6%) inside the enclosure. Where we find values between a maximum value corresponding to the end of the enclosure (upper wall) and a low value corresponding to the temperature at the bottom of the enclosure wall inferior. It can be seen in the figure that the temperature increases with increasing altitude, just after the position Y = 0.01. The figure consists of two distinct areas, from Y=0 to Y=0.01. The temperature increases with the increase in altitude and remains almost constant then just after the position Y = 0.01 the temperature increases significantly, up to the value of the upper wall. Further also show that the product enhancement of entropy generation and heat transfer increases significantly with increasing Reynolds number.

The profiles of the velocity at mid-length of the cavity for the different Richardson numbers chosen are shown in (fig.7) we note that the maxima are proportional to the number of Ri and that its positions are closer to the wall hot when in fact increase the number of Ri. This is due to the combined effects of jet convection and thermal buoyancy along the horizontal direction where boundary layers become thicker with flow intensification. However, the maximum speed values are encountered in the interval 0.0<X<0.6. These values indicate where fluid particles follow moving streamlines.

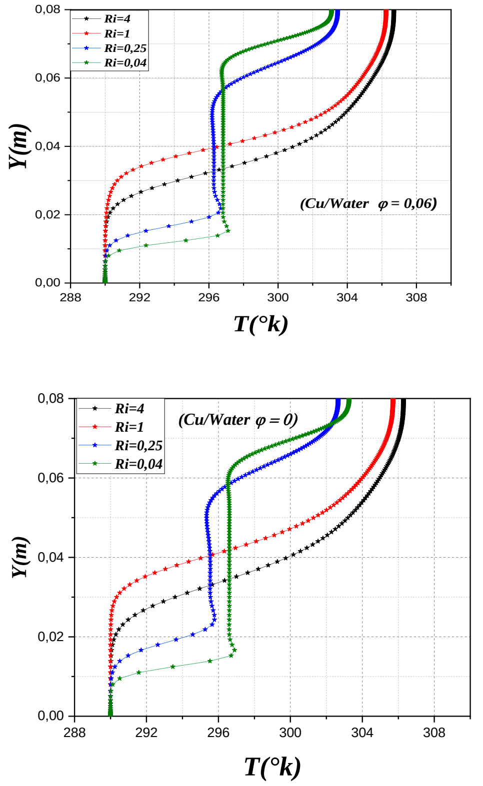


Fig. 6, Temperature profile along different altitudes of the (Cu/Water) enclosure, for different Richardson numbers (*Ri*), x= 0.5H.

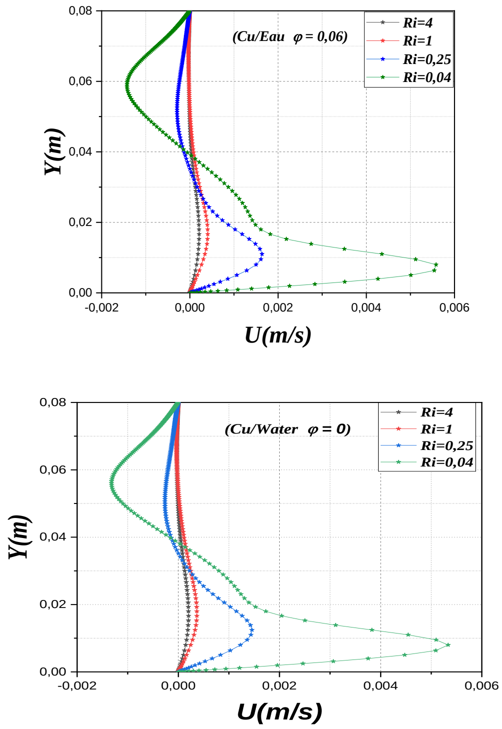
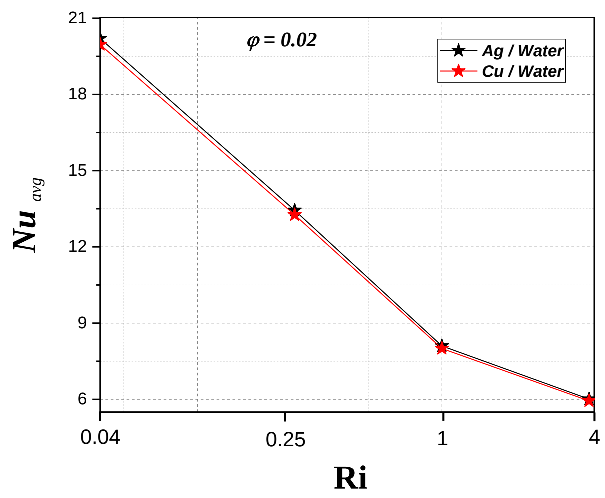
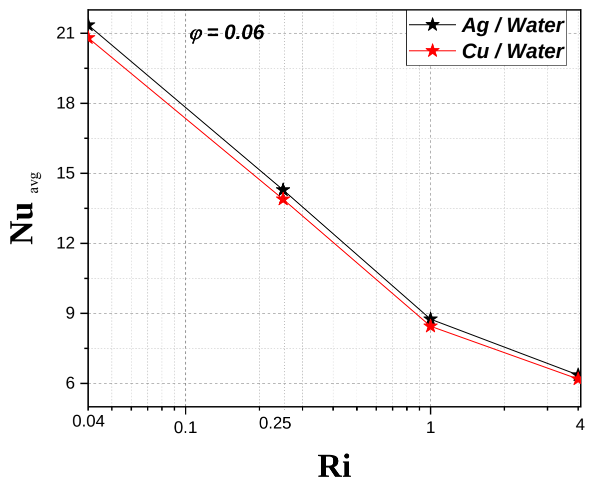


Fig. 7, Profile of transverse velocities along the axis (Y) of the enclosure for different Richardson numbers, x = 0.5 H.

4.3 Effect of nanoparticle types

The heat transfer made it possible to trace the average and local Nusselt numbers at the level of the hot right vertical wall. The variation of the average Nusselt number as a function of the Richardson number for different types of nanofluids (Nanoparticles) is shown in (fig.8). The maximum value of the Nusselt number is obtained for the smallest value of ***Ri***. Where one notices that the rate of reduction of the total production is more important in the case where the value of the number of ***Ri*** is higher, this is justified by the presence of the weak temperature gradient inside the cavity, which influenced the decrease, and production of heat transfer rate. On the other hand, we notice that the total Nusselt number decreases linearly with the increase of the volume fraction of the nanofluid. In addition, it was observed that the type of nanofluid added, and that Ag is the most effective nanoparticle in increasing the heat exchange rate, because according to Maxwell's equation (1873), the type of nanofluid motivates thermal conductivity, and gives a significant improvement in heat transfer. From the figure, it has been noticed that (***Cu***) has the lowest thermal conductivity value compared to the other nanoparticle, hence, it exhibits low Nusselt number values. So, we can say that the Nusselt number reaches its maximum when using silver ***Ag*** as nanoparticles, on the other hand, reaches its minimum after using copper ***Cu***.





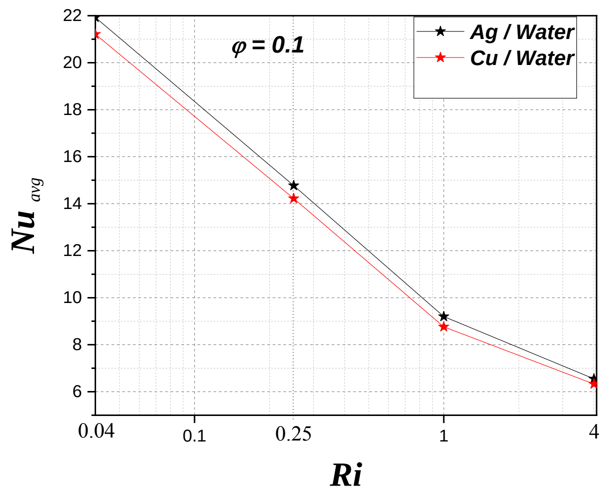


Fig. 8, Variation of the average Nusselt number for the different Richardson numbers Ri.(φ=2%, 6% and 10%), Gr = 10^4.

4.4 Effect of nanoparticle concentration

(fig.9). Exposes the variation of the average Nusselt number for different Richardson numbers and nanofluids, depending on the different solid volume fractions of the nanoparticles. We find that in all cases, the average Nusselt number is an increasing linear curve that increases with an increasing solid volume fraction of nanoparticles in the heat transfer fluid. In addition, it was detected that the highest values of the average Nusselt number were found for a Richardson number Ri = 4 and that the lowest value of the average Nusselt number was obtained for a Ri = 0.04. The figure also shows that the average Nusselt number increases with increasing volume fraction, the maximum of the average Nusselt number is found with the volume fraction of 10%.

The transverse velocity profile as a function of (Y) at mid-length (x = 0.5 H) in the cavity for the different solid volume fractions of nanoparticles for the nanofluid (Ag/Water) with Richardson numbers Ri=1 is shown in (fig.10). Note that the flow field is made up of two zones. The first zone starts from the bottom wall at y=0 to y=0.02. The second zone starts from y=0.02 and ends at the top wall, with a uniform velocity profile at a parabolic pace, this indicates that the maximum velocities are essentially located in the middle of the two zones, but in opposite directions i.e. One with positive values and one with negative values. We also note the presence of negative values of speed U, which translates to the presence of a recirculation zone in the cavity, which makes it possible to note the presence of the vortex. Note that for a basic fluid (φ = 0%) for example, the vertical speed is 0.000375 m/s, while it decreases to - 0.000033 m/s. When increasing the volume fraction of nanoparticles from 0% to 8%, with a reduced rate of 67%. This indicates that density affects the speed reduction by a large percentage. This means that the greater the proportion of volume fractions in the nanofluid, the greater the density in the case where the convection is mixed.

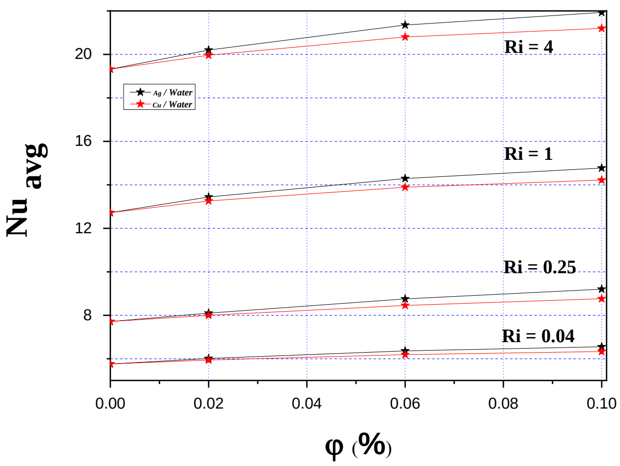


Fig. 9, Variation of the average Nusselt number for the different Richardson numbers, Ri, and nanofluids, according to the different volume fractions (φ%).

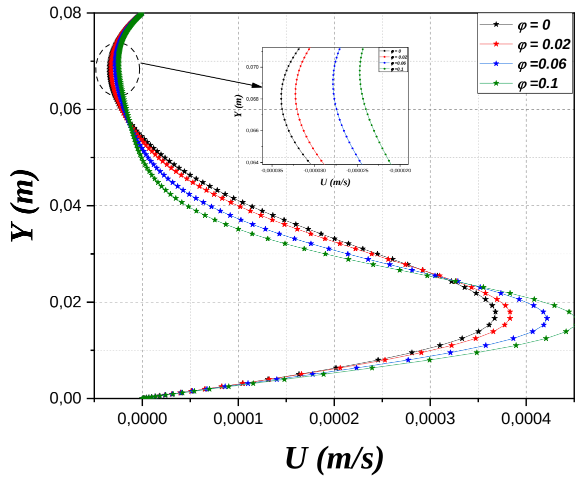


Fig. 10, Profile of the transverse velocities along the axis (*Y*) of the enclosure for different volume fractions at *x = 0.5 H, (Ag/Water), Ri =1.*

5 Conclusion

In the present work, the finite volume method is used to numerically solve the problem of mixed convection in a ventilated square cavity. The cavity is filled with different nanofluids, and contains two gates (Orifices) for entering and exiting the flow. It presents, examines and explains the thermal and dynamic characteristics of the flow for the aspects of fixing the Grashof number at 10^4, and varying the Reynolds number. The numerical results obtained show a multicellular stationary flow regime whose Cell size and shape are strongly dependent on Grashof number and Reynolds number. An in-depth analysis has been carried out in which the equations for the conservation of mass, motion and energy and the generation of entropy are solved using the ANSYS FLUENT 6.3 computer code. A comparison has been made with results from work published by Sumon Saha et al. [9], to validate our work. A good agreement was obtained. The effects of Richardson number, nanoparticle volume fraction, and nanofluid type on fluid flow, and thermal performance have been studied in detail.

The main results can be summarized as follows:

- The difference in heat transfer, using different nanofluids, increases with the increase in the value of the volume fraction of the nanoparticles.

- The existence of nanoparticles means an improvement in the rate of heat transfer which is indicated by the increase in the Nusselt number.
- The effect of the nanofluid on the convection manifests itself, particularly at a high Richardson number.
- It can be seen that the Nusselt number increases with the increase in the Richardson number and the volume fraction for different volume concentrations of nanoparticles.
- nanofluids which contain nanoparticles of metallic types and of high thermal conductivity compared with that non-metallic nanoparticles.

References:

[1] Aghaei, H. Khorasanizadeh, G. Sheikhzadeh, M. Abbaszadeh, Numerical study of magnetic field on mixed convection and entropy generation of nanofluid in a trapezoidal enclosure, 22 Journal of Magnetism and Magnetic Materials, 403 (2016) 133–145.

[2] S. Choi, Enhancing thermal conductivity of fluids with nanoparticles, in: D.A. Signier, H.P. Wang (Eds.), Development and Applications of Non Newtonian Flows, Vol. 66, ASME FED, vol.231/MD 99–105 (1995).

[3] N. A. C Sidik, I. M. Adamu, M. M. Jamil, R. , G.H.R. Kefayati, R. Mamat, G.Najafi, Recent progress on hybrid nanofluids in heat transfer applications: A comprehensive review, International Communications in Heat and Mass Transfer, 78 (2016) 68–79.

[4] S. MOJUMDER, S. SAHA, S. SAHA, M. A. H MAMUN, Combined effect of Reynolds and Grashof numbers on mixed convection in alid-driven T-shaped cavity filled with water-Al2O3nanofluid, Journal of Hydrodynamic,27 (5) (2015) 782–794.

[5] I. Tmartnhad, M. El Alami, M. Najam, A. Oubarra, Numerical investigation on mixed convection flow in a trapezoidal cavity heated from below, Ener. Conv. Management, 49 (2008), 3205-3210.

[6] E. Sourtiji, M. Gorji-Bandpy, D.D. Ganji, S.F. Hosseinizadeh Numerical analysis of mixed convection heat transfer of Al2O3-water nanofluid in a ventilated cavity considering different positions of the outlet port, Powder Technology, 262 (2014) 71-81.

[7] M.Shahi, A. Houshang Mahmoudi, F. Talebi, Numerical study of mixed convective cooling in a square cavity ventilated and partially heated from the below utilizing nanofluid, Int. com. In heat and mass tranf, 37 (2010) 201-213.

[8] K. Kalidasan , P. Rajesh Kanna, Natural convection on an open square cavity containing diagonally placed heaters and adiabatic square block and filled with hybrid nanofluid of nanodiamond -cobalt oxide/water, International Communications in Heat and Mass Transfer, 81 (2017) 64–71.

[9] Sumon Saha, Md. Tofiqul Islam. Mohammad Ali. Md Arif. Hasan Mamun and M. Quamrul Islam, effect of inlet and outlet locations on transverse mixed convection inside a vented enclosure. Journal of mechanical engineering, vol. me36, transaction of the mech. Eng. div., the institution of engineers, Bangladesh,Dec. (2006).