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Original Article

MHD natural convection in a cavity partially heated having a wavy wall and filled with Al_2O_3-water nanofluid

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ABSTRACT

This study focuses on the coupling of MHD natural convection in a cavity filled with Al_2O_3-water nanofluid. The cavity consists of vertical walls maintained at the temperature T_c, while the horizontal ones are adiabatic. The source is fixed at a high temperature T_h and one of vertical walls is corrugated. Ansys Fluent software based on finite volume method was used to solve different transport equations through the use of a monophasic model. Several pertinent parameters were considered in the present study, such as Rayleigh number ($7.68.10^4 \le Ra \le 3.072.10^5$), Hartmann number ($0 \le Ha \le 75$), and solid volume fractions ($0 \le \varphi \le 0.05$). The influence of these parameters on heat transfer and flow structure was analyzed by examining streamlines, isotherms, velocity and temperature profiles, and Nusselt numbers. Based on the results obtained, we notice that heat transfer enhancement rises with both Rayleigh number and nanoparticle volume fraction, but it decreases when Hartmann number increases. Also, we note that the conduction heat transfer becomes significant and that by convection becomes limited and sometimes suppressed for high values of the Hartmann.

1. Introduction

In recent years, many industrial heating and cooling applications are based on convective heat transfer. This mode of heat transmission becomes effective by modifying certain parameters such as heat exchange surface, coolant,… etc. The use of nanofluids as heat transfer fluids improves the thermal performance of energy systems.

The study of nanofluid flow and heat transfer by convection in cavities of different shapes and in particular partially heated corrugated ones has received considerable importance in many research works. Among the authors who have carried out studies in this research activity, we can cite Saidi et al., [1] who conducted an experimental and numerical study of the flow structure and heat transfer inside a corrugated cavity. They found that the presence of a vortex reduced the total heat exchange between the moving fluid and the corrugated cavity wall. Adjlout et al., [2] conducted a numerical investigation of free convection in a cavity having an angle with the horizontal, a hot corrugated wall and a flat cold one. It was noted that heat transfer decreased with the corrugation of the enclosure wall compared to the flat-walled one. Other studies of free convection in rectangular enclosures heated from below, cooled symmetrically from the sides and saturated with air, have been carried out numerically and experimentally by Ganzarolli and Milanez [3], Aydin and Yang [4]. , Sharif and Mohamed [5], Calcagni et al., [6].

Conventional fluids (water, ethylene glycol, etc.) which are used in different thermal systems as heat transfer fluids are limited in their use. Advances in nanotechnology have developed new techniques that make it possible to have fluids with better thermal properties.

The process of obtaining these fluids consists of suspending solid particles of nanometric sizes in the classical fluids and the resulting fluid is called nanofluid

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and the first researcher who invented this type of fluids is Choi [7].

Many researchers are oriented towards nanofluids because they offer the possibility of improving energy systems efficiency, such as cooling of electronic components, solar collectors,… etc.

In this research activity, several investigations have been developed, among which, we can mention that of Khanafer et al., [8], who carried out a numerical study on the improvement of heat transfer in a saturated two-dimensional geometry of a nanofluid. They noted that heat transfer rate is proportional to the volume fraction of the nanoparticles for all given Grashof numbers. Tiwari and Das [9] have numerically studied mixed convection in a square enclosure differentially heated and saturated with nanofluid. Abu-Nada and Oztop [10] numerically analyzed the influence of the angle of inclination on free convection and fluid flow in an enclosure saturated with Cu-water nanofluid. Alizadeh et al., [11] presented a numerical study on heat transfer by mixed convection in a heated square cavity, filled with a nanofluid and having an inlet and an outlet.

In their numerical investigation, Rahmoune and Bougoul [12] studied laminar mixed convection of Al_2O_3-H_2O nanofluid in a square section channel exposed to a constant heating flux. Their results show that heat transfer rate increases with an increase in Reynolds number and volume fraction of the nanoparticles, but it decreases with an increase in the modified Richardson number.

Another study of laminar natural convection was carried out by Rahmoune et al., [13] in an enclosure with a geometry slightly different from that in H and saturated with Al_2O_3-water nanofluid. it was observed that with increasing nanoparticle volume fraction and Rayleigh number, the average Nusselt number inside the cavity increases.

Other research work has been devoted to the study of heat transfer under the effect of the magnetic field inside cavities of different shapes and saturated with nanofluids, we find those of Mahmoudi et al., [14], Ghasemi [15] and Elshehabey et al., [16] who studied the natural convection of a nanofluid under the influence of a magnetic field in triangular, U-shaped and L-shaped cavities respectively. They noted that adding the nanoparticles to the base fluid improves the heat transfer rate, but the presence of the magnetic field reduces the intensity of natural convection.

Sheikholeslami et al., [17] analyzed the natural convection of the CuO-water nanofluid in a cavity with a sinusoidal wall subjected to a constant heat flux in the presence of a magnetic field. They observed that the Nusselt number increases with the volume fraction of the nanoparticles and the amplitude of the sinusoidal wall as well as the Rayleigh number, however it decreases with the Hartmann number.

Öğüt et al., [18] carried out a numerical simulation of the natural convection of a nanofluid in an inclined cavity with corrugated walls. Ma et al., [19] studied the magnetohydrodynamic natural convection of CuO-water nanofluid in a hollow cavity using the Lattice-Boltzmann method.

The influence of the magnetic field on the natural convection of a hybrid nanofluid in a square enclosure provided with a corrugated circular cylinder was investigated by Tayebi and Chamkha [20].

Alsabery et al., [21] examined heat transfer by free convection in a corrugated porous cavity saturated with a nanofluid considered as non-Darcian. They noted that the existence of undulations on the vertical walls leads to a decrease in heat transmission when convection is dominant, while it increases when conduction is important.

Al-Kouz et al., [22] presented a study on free convection and entropy production in a corrugated cavity saturated with a hybrid nanofluid, filled with a porous medium and subjected to a magnetic field. They found that entropy generation and average Nusselt number increase with increasing Rayleigh number and decrease with increasing Hartmann number. Abu-Libdeh et al., [23] examined natural convection and total entropy under a constant magnetic field in a cavity filled with a porous medium and saturated with the hybrid nanofluid.

Saeed Nazari et al., [24] developed a numerical study on the mixed flow of the non-Newtonian water-Al_2O_3 nanofluid inside a two-dimensional square cavity with hot and cold lid motion and in the presence of a porous medium. In this work, they studied the effect of volume fraction and Darcy and Richardson numbers on the dynamic and thermal behavior of the flow.

Ahmed Albojamal et al., [25] analyzed the laminar forced convection and pressure drop of Al_2O_3 and CuO-water nanofluids flow through a horizontal tube and a corrugated channel under boundary conditions of constant wall temperature. The impact of parameters, such as particle concentration, particle diameter, particle type, constant or temperature dependent properties, wave amplitude, Reynolds number and Peclet number on the thermal and flow fields of the nanofluids is studied. The results obtained show that the variable properties assumption plays a dominant role and provides better predictions for the enhancement of heat transfer.

A numerical analysis of entropy production and free convection flow in a hollow enclosure having a specified shape, subjected to a magnetic field and saturated with Al_2O_3-water nanofluid was developed by Rahmoune and

Bougoul [26]. In this study, entropy production and average Nusselt number increase with Rayleigh number and nanofluid concentration but they decrease with Hartmann number.
In this work, we present a numerical simulation of heat transfer by laminar natural convection of an alumina/water nanofluid inside a cavity having a corrugated right wall and subjected to the action of a magnetic field. The main objective of this study is to determine the thermal and dynamic behavior of the nanofluid flow inside the corrugated cavity and to see the effect of the magnetic field on flow structure and heat transfer rate by varying different control parameters such as Rayleigh number, Hartmann number and concentration of Al_2O_3-water nanofluid.

2. Physical model

Effect of MHD on natural laminar convection inside a square enclosure having a right corrugated wall and filled with Al_2O_3-water nanofluid is investigated. This study is based on the single-phase model. Two-dimensional geometry with boundary conditions chosen and imposed on different walls is represented in figure 1. Heat source of length B is placed on the lower wall with a temperature (T_h) and the rest of the horizontal walls are considered adiabatic, while the corrugated right wall and the left vertical one are maintained at the cold temperature (T_c). No-slip condition is imposed on all the walls of the cavity. The nanofluid chosen in this study is assumed Newtonian, incompressible and the flow is considered laminar and stationary. Effects of radiation and viscous dissipation are neglected. All the physical characteristics of the considered nanofluid are supposed constant except the density which is taken variable by introducing the Boussinesq approximation in the momentum equation. Horizontal external magnetic field is imposed on the enclosure.

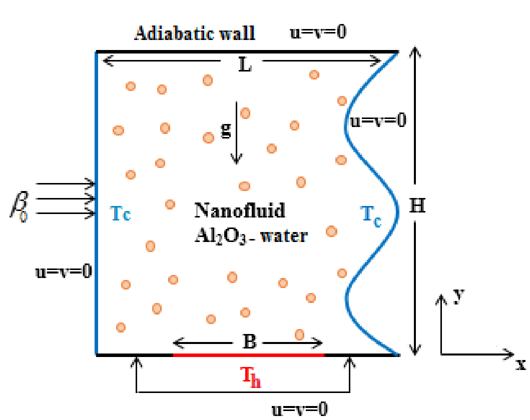


Fig 1. Studied geometry.

Governing equations of natural convection in the cavity in cartesian coordinates, are continuity, momentum and energywhich they can be written as:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial P}{\partial x}+\upsilon_{nf}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \qquad (2)$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial P}{\partial y}+\upsilon_{nf}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+Fy \qquad (3)$$

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

In which, Fy represents total body forces in the y direction, it is defined as follows:

$$Fy=\beta_{nf}\,g\,(T-T_C)-\frac{\sigma_{nf}}{\rho_{nf}}\beta_0^2 v \qquad (5)$$

With: ρ_{nf} is density, υ_{nf} the kinematic viscosity, β_{nf} its thermal expansion coefficient, and α_{nf} is the thermal diffusivity of the nanofluid, σ_{nf} and β_0 are electrical conductivity and magnetic field respectively.
The conventional formulas that are developed for mixtures of solids and liquids can be employed to determine several properties such as thermal conductivity K_{nf}, viscosity μ_{nf}, density ρ_{nf}, thermal expansion coefficient β_{nf} and nanofluid specific heat Cp_{nf} [12 ,27].

$$K_{nf}=\left[\frac{K_s+2K_f-2\varphi(K_f-K_s)}{K_s+2K_f+\varphi(K_f-K_s)}\right]K_f \qquad (6)$$

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

$$\rho_{nf}=(1-\varphi)\rho_f+\varphi\rho_s \qquad (8)$$

$$(\rho\beta)_{nf}=(1-\varphi)(\rho\beta)_f+\varphi(\rho\beta)_s \qquad (9)$$

$$(\rho cp)_{nf}=(1-\varphi)(\rho cp)_f+\varphi(\rho cp)_s \qquad (10)$$

Electrical conductivity σ_{nf} can be calculated using the following formula [26]:

$$\sigma_{nf}=\left[1+\frac{3\varphi(\gamma-1)}{(\gamma+2)-(\gamma-1)\varphi}\right]\sigma_f \qquad (11)$$

Where: $\gamma = \dfrac{\sigma_s}{\sigma_f}$

In this study, non-dimensionless parameters include:

$$Ra = \frac{g\beta_{nf}\left(T_h - T_c\right)H^3}{\upsilon_{nf}\alpha_{nf}}, \quad Nu = \frac{h_{nf}H}{K_{nf}}, \quad Ha = \beta_0 H\sqrt{\frac{\sigma_{nf}}{\mu_{nf}}}$$

Ra, Nu and Ha are numbers of Rayleigh, Nusselt and Hartmann respectively.

In magnetohydrodynamics coupled to natural convection, Hartmann number is a crucial quantity, it represents electromagnetic force compared to the viscous one. It characterizes fluids movement having a certain conductivity and exposed to a magnetic field [27].

3. Numerical model

In this study, the system of equations (1), (2), (3) and (4) which governs the physical phenomenon to be studied is solved using the commercial software Fluent-CFD, which uses the finite volume approach. The pressure-velocity coupling is assured by the SIMPLE algorithm, while the convective-diffusive terms are discretized using the second-order Upwind scheme. A convergence criterion of 10^{-6} is set for the numerical solution of the continuity, momentum, and energy equations respectively.

3.1. Mesh independence test

The cavity considered is meshed with a structured, refined, uniform and quadratic mesh, which makes it possible to capture all the gradients which occur in contact with the walls. In any numerical study, it is important to test the independence of the results obtained from the selected mesh before interpreting them. For Ra = $7{,}68.10^4$, three different mesh types were considered (11495), (12573) and (13936) (numbers of cells). In Figure 2(b), we have plotted the temperature profiles near the bottom wall of the cavity for these three mesh types.

To reduce computation time and ensure good precision, we have chosen the second mesh (12573).

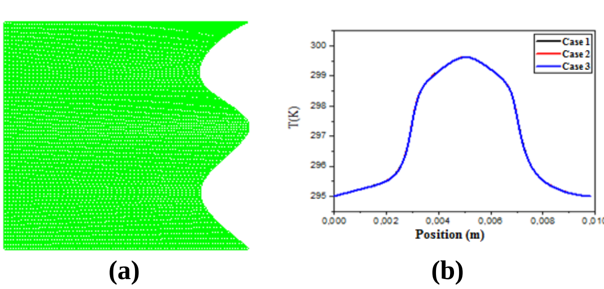


Fig 2. (a) Mesh used, (b) Temperature profile for the selected meshes.

3.2 Validation of the numerical method

To verify the numerical method used and validate our results, we started our numerical calculation with a study of heat transfer in a cavity having same shape, same boundary conditions and same working fluid as that used by Calcagni et al., [6] and Aydin et al., [4].

In Figure 3, the qualitative comparison of isotherms and streamlines shows a good agreement between our results and those obtained by these authors for different Rayleigh numbers.

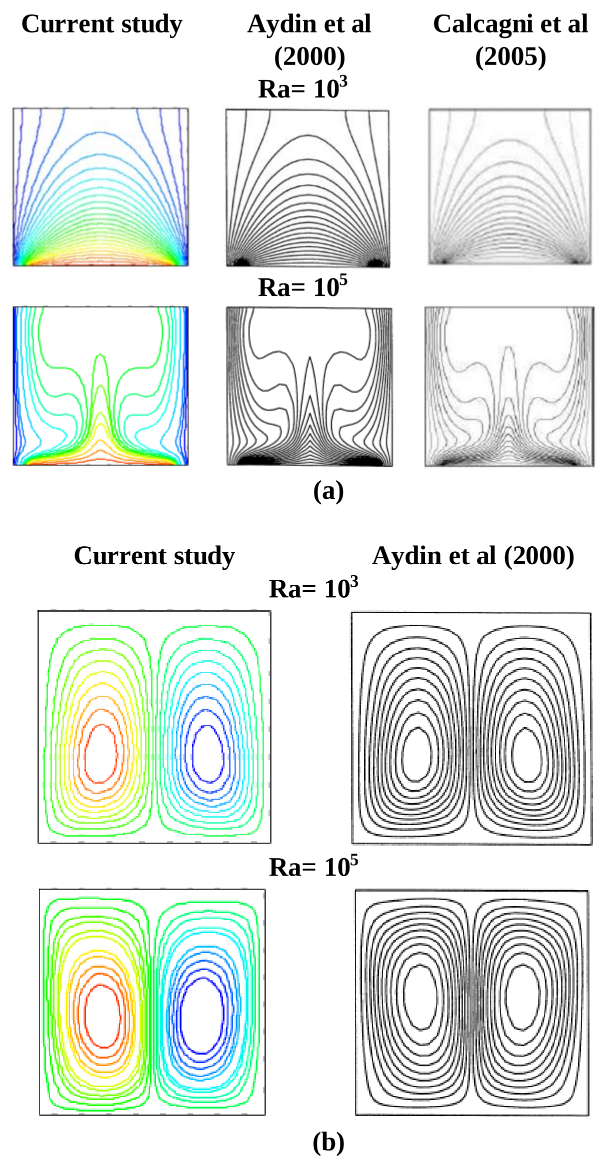


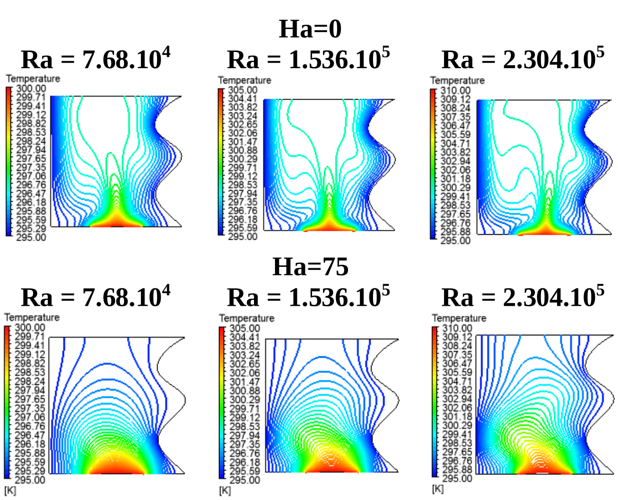
Fig 3. Results validation. (a) Isotherms distribution and (b) Streamlines distribution.

4. Results and discussions

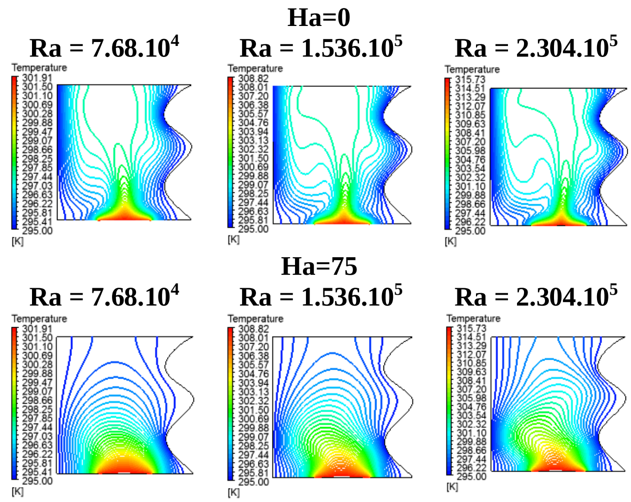
In this section, we will see the influence of different physical parameters on the main results obtained. First, it is useful to give the variation interval of these parameters, namely Rayleigh number ($7.10^4 \leq Ra \leq 2.5.10^5$), Hartmann number ($0 \leq Ha \leq 75$) and nanoparticles volume fraction ($0 \leq \varphi \leq 0.05$). Water is considered as the basic fluid of this study.

4.1. Temperature variation

Temperature variation for different Hartmann numbers, Rayleigh numbers and for the chosen volume fractions, is shown in Figure 4. It can be seen that the thickness of the thermal boundary layer near the hot wall decreases with an increase in Rayleigh number, the intensity of convection is more important than conduction and the isotherms become more stratified. It can also be seen that the isotherms are not symmetrical with respect to the vertical axis passing through the center of the cavity, this is due to the presence of a corrugated vertical wall. Increasing the volume fraction of the nanoparticles increases the temperature of the nanofluid relative to that of the base fluid without changing the flow structure. When a magnetic field is imposed, the Hartmann number has a noticeable effect on the isotherms, especially at low values of the Rayleigh number. As the Hartmann number increases, the isotherms condense and become parallel to each other. This phenomenon is the result of heat transfer by conduction which is dominant compared to that by convection which becomes limited or suppressed.



(a) φ=0%.



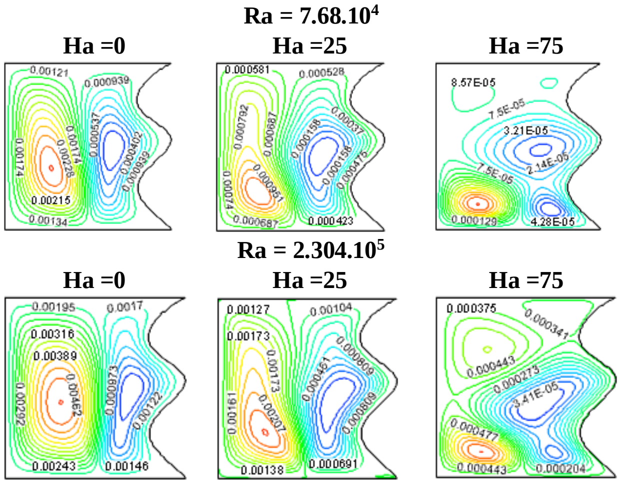
(b) φ=5%.

Fig 4. Isotherms distribution for different Rayleigh numbers and Hartmann numbers.

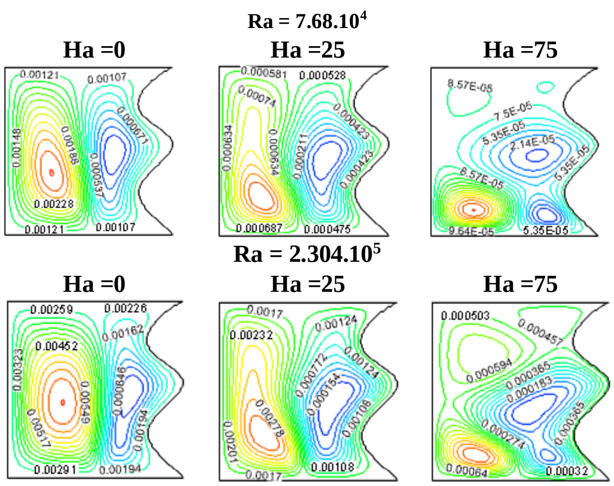
4.2. Velocity variation

4.2.1 Streamlines

In Figure 5, we present the impact of Rayleigh number, volume fraction and Hartmann number on the contours of the streamlines. At a chosen Rayleigh number, two counter-rotating cells occur inside the cavity when the Hartmann number is equal to zero. If Rayleigh number increases, the fluid occupies more space in the enclosure and if the volume fraction of the nanofluid increases flow structure is not affected, but the fluid becomes accelerated. Application of a magnetic field changes flow structure and slows down the fluid movement which occupies less space in the cavity. For a high Hartmann number, we note the production of other vortices and we observe that fluid movement takes place along the lower wall of the cavity. We also find that the value of the stream function increases with the increase in the Rayleigh number and decreases with the increase in the Hartmann number.



(a) φ=0%.



(b) φ=5%.

Fig 5. Streamlines for selected Rayleigh numbers and Hartmann numbers.

4.3. Velocity profiles

The impact of different Hartmann numbers on the vertical velocity profiles for two Rayleigh numbers and two volume fraction values (0% and 5%) is shown in figure 6. The profiles are located at the bottom, near the horizontal wall of the enclosure. For Ha = 0, we noted that the fluid velocity increases with the increase of the Rayleigh number and nanoparticles volume fraction, consequently, this favors the increase of the convection intensity. By applying the magnetic field, the effect of Hartmann numbers is more remarkable at low Rayleigh numbers where the velocity can decrease to zero values unlike at large Rayleigh numbers. An increasing in Hartmann number leads to a reduction in the velocity component which implies that the intensity of the convection becomes limited and the conduction becomes significant.

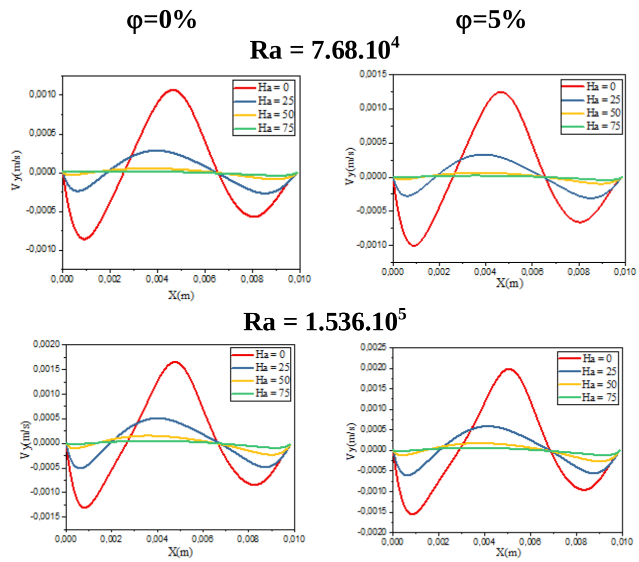


Fig 6. Vertical velocity component for selected Rayleigh numbers and volume fraction and for different values of Hartmann numbers.

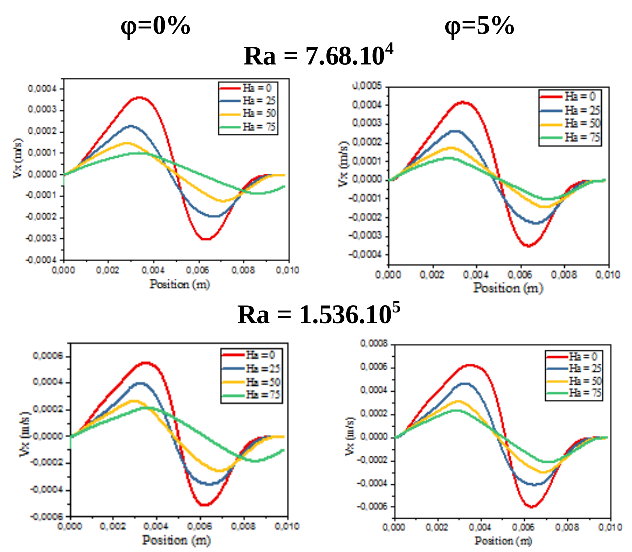


Fig 7. Horizontal velocity components for selected Rayleigh numbers and volume fraction and for different values of Hartmann numbers.

The horizontal component of the velocity is represented in figure 7. The effect of the different parameters (volume fraction, Rayleigh and Hartmann numbers) on this velocity component is the same as that of the vertical component.

4.4. Temperature profiles

In figure 8, we represent the temperature variation near the lower wall of the studied cavity. We find that temperature increases with increasing Rayleigh numbers and nanoparticle concentrations. It can be seen that the intensity of the convection is weakened due to the presence of a magnetic field. The Lorentz force slows down the fluid motion and leads to the dominance of the conductive heat transfer mechanism.

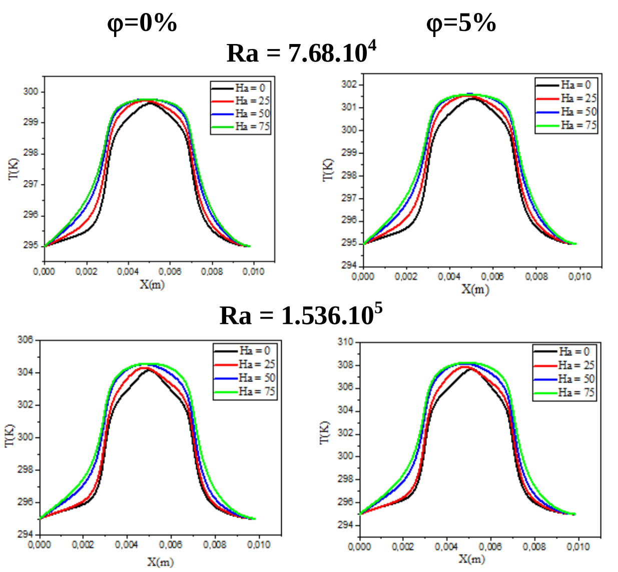


Fig 8. Temperature variation for selected Rayleigh numbers and volume fraction and for different values of Hartmann numbers.

4.5. Nusselt number

The effects of the Rayleigh number, the Hartmann number and the volume fraction of the nanofluid on the local Nusselt number along the wall where the source is applied are shown in figure 9. We find that the local Nusselt number increases with increasing Rayleigh number and volume concentration, but decreases with increasing Hartmann number. At the edge of the source boundaries, we notice that the local Nusselt number takes maximum values due to high temperature gradients with intense fluid recirculation. However, it decreases at the center of the source due to the development of a small temperature gradient. The minimum local Nusselt value is noted at Ha = 75 which is related to the dominance of conduction in this region.

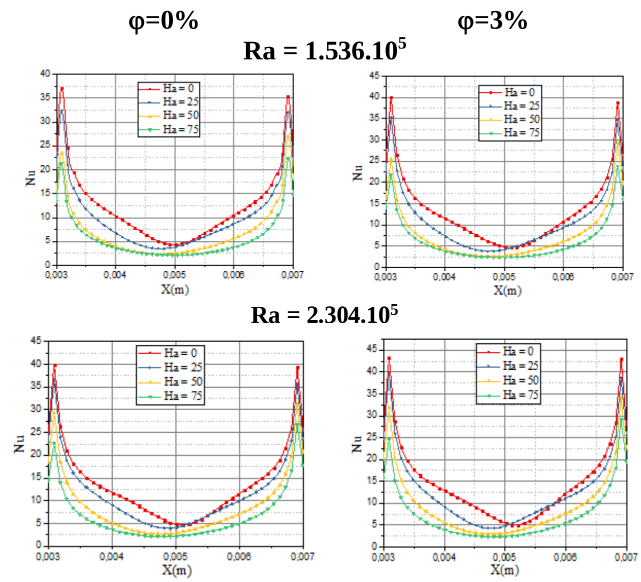


Fig 9. Variation of the local Nusselt as a function of the Hartmann number for different Rayleigh numbers and for two values of the volume fraction.

The influence of various parameters on the mean Nusselt number is illustrated in figure 10. We can see that in the absence of a magnetic field, the average Nusselt number is an increasing function of the Rayleigh number and nanoparticle volume friction where a higher value of Nusselt number will be obtained at Ha=0. The effect of nanoparticles is more noticeable on average Nusselt at high Rayleigh numbers than at low ones. This is due to the increased thermal conductivity of nanoparticles that contribute to the improvement of heat transfer. However, in the presence of a magnetic field, an increase in the Hartman number results in a decrease in the heat transfer rate. We conclude that, there is a reveres relationship between the Nusselt number and the Hartmann number.

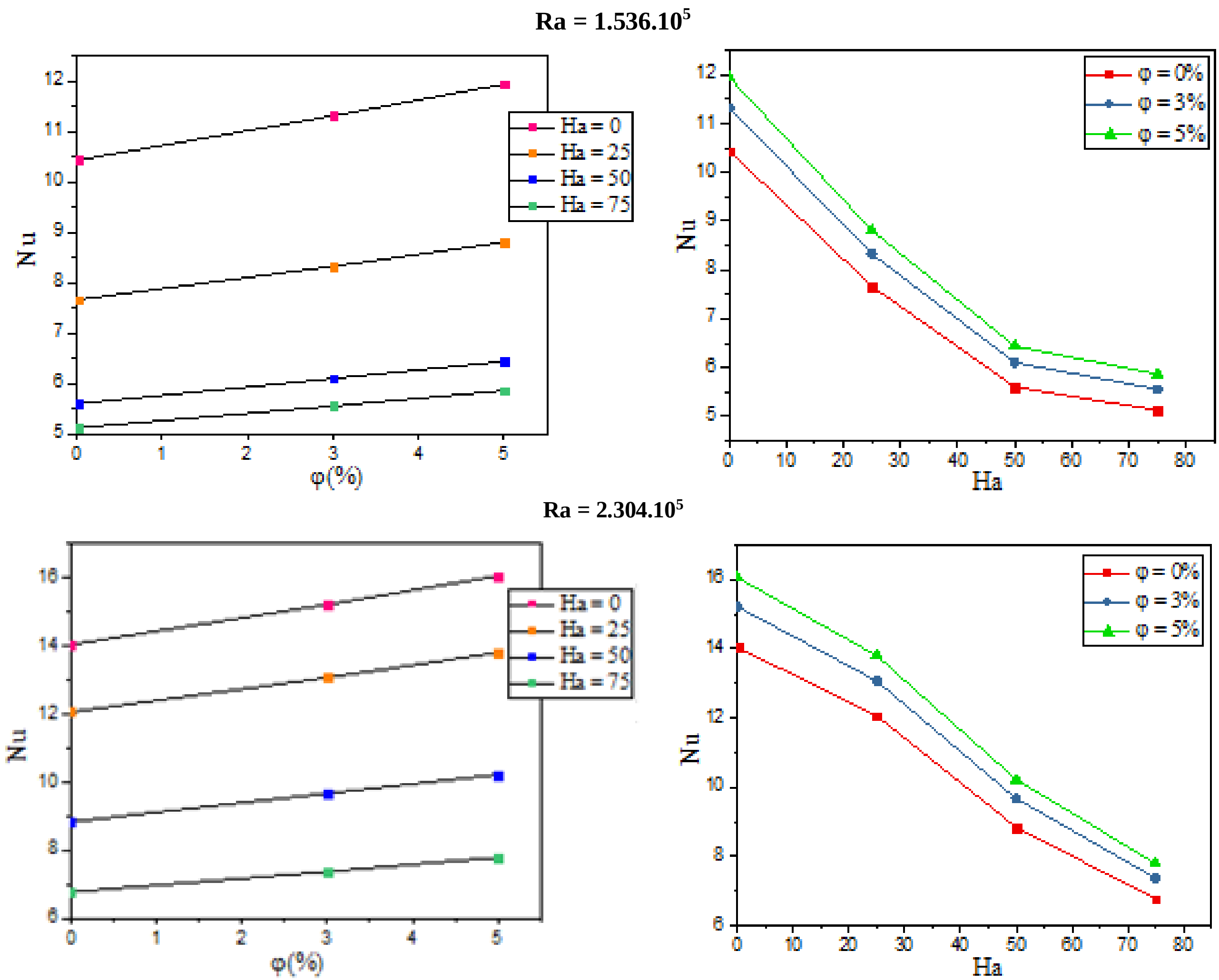


Fig 10. Variation of the average Nusselt as a function of the Hartmann number for different Rayleigh numbers and for two values of the volume fraction.

5. Conclusions

The influence of magnetohydrodynamics on the heat transfer by natural convection in an enclosure having a corrugated vertical wall partially heated from below and saturated with nanofluid is examined numerically in this work. Numerical results were obtained for various values of the Rayleigh number, the concentration of Al_2O_3 nanoparticles and the Hartmann number. The influence of these parameters on isotherms, streamlines and Nusselt number is presented and analyzed.

Based on the results of this study, the following conclusions can be drawn:

❖ The intensity of heat transmission by convection becomes more important as the Rayleigh number increases.

❖ The thermal boundary layer thickness around the hot wall decreases with an increase in the Rayleigh number and nanoparticle volume fraction.

❖ The increase in the Hartmann number decelerates the movement of the fluid due to the action of the Lorentz force, where the intensity of convection weakens considerably.

❖ The Nusselt number grows with increasing Rayleigh number and volume fraction of nanoparticles and declines with increasing Hartmann

❖ The undulations favor heat transfer, but they impede fluid movement along the wall.

❖ The magnetic field can limit heat transmission by convection at high Hartmann numbers, whereas conduction becomes predominant.

❖ The coupling of MHD with free convection significantly affects fluid motion.

Nomenclature

β_0:	Uniform magnetic field	[Tesla]
B:	Length of hot source part	[m]
Cp:	Specific heat at constant pressure	[$J.kg^{-1}.K^{-1}$]
g:	Gravitational acceleration	[$m.s^{-2}$]
h:	Convection heat transfer coefficient	[$W.m^{-2}.K^{-1}$]
H:	Height of the enclosure	[m]
Ha:	Hartmann number	[-]
K:	Thermal conductivity	[$W.m^{-1}.K^{-1}$]
L:	Length of the enclosure	[m]
Nu:	Average Nusselt number	[-]
Ra:	Rayleigh number	[-]
T:	Temperature	[K]
u, v:	Velocity components	[$m.s^{-1}$]

Greek Symbols

α:	thermal diffusivity	[$m^2.s^{-1}$]
ρ:	density	[$kg.m^{-3}$]
β:	coefficient of thermal expansion	[K^{-1}]
σ:	Electrical conductivity	[$\Omega^{-1}.m^{-1}$]
μ:	dynamic viscosity	[$Kg.m^{-1}.s^{-1}$]
ν:	kinematic viscosity	[$m.s^{-2}$]
φ:	volume fraction	[%]

Subscripts

f:	fluid
s:	nanoparticle
nf:	nanofluid
c:	cold wall
h:	hot wall

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