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EFFECTS OF MAGNETIC FIELD DIRECTION AND NANOPARTICLES CONCENTRATION ON FREE CONVECTION IN A VERTICAL CYLINDER

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ABSTRACT

In this work, the effect of the magnetic field direction on laminar stationary convection heat transfer in a vertical cylinder filled with a CuO nanofluid is numerically studied. The magnetic field externally applied to the cylinder is once directed axially (Bz) and a second time directed radially (Br). The cylinder having an aspect ratio $H/R_0 = 3$, is limited by two upper and lower walls at constant temperatures respectively cold Tc and hot Th and by an adiabatic sidewall. The equations of continuity, Navier Stocks and energy are non-dimensionalized and then discretized by the finite volume method. A computer program based on the SIMPLER algorithm is developed and compared with the numerical results found in the literature. The effects of the direction and intensity of the magnetic field on the dynamic field, on the thermal field and on the average Nusselt number are presented and discussed through the variation of the Hartmann number $(Ha = 0, 5, 10, 15, 20, 30 \dots .60)$, as well as the effect of the nanoparticles volume fraction $(\emptyset = 0, 0.025, 0.05, 0.075, 0.1)$ and this for three values of Rayleigh number ($Ra = 10^3$, 5×10^3 and 10^4). The results found show that the average Nusselt number increases with the increase in the Rayleigh number but it decreases with the increase in the Hartmann number. Depending on the magnetic field direction and on the values of Hartmann and Rayleigh numbers, an increase in the volume fraction of the nanoparticles in the nanofluid may cause an enhancement or deterioration in the heat transfer performance in the nanofluid.

Keywords: *Natural convection, nanofluid, magnetic field, Reynolds, Nusselt, finite volume method, numerical simulation.*

INTRODUCTION

Convective heat transfer enhancement has been a challenging topic of interest for researches for many years because of the wide applications in engineering and industry such as nuclear reactor design, cooling system in electronic components, solar systems, thermal storage system and vapor condenser for water distillation and food process. The problem of the low thermal conductivity of the working fluid such as air and water used in the thermal equipment has been solved by adding ultra-fine solid particles in the base fluids [1].

In addition, the use of magnetic field in thermal process provides more opportunities for a wide range of applications such as preparation of magnetic fluid, data storage, biomedical science, crystal growth of semi-conductors, material manufacturing and the geothermal energy extraction. The application of external magnetic field decreases the heat transfer rate and the use of nanofluid enhances the heat transfer in the enclosure. In some engineering systems like the magnetic field sensors, the magnetic storage media and the cooling systems of electronic equipment, the application of magnetic field is necessary and the enhanced heat transfer rate is desirable.

The idea of using nanofluids as working fluid in an enclosure to improve the heat transfer performance in such devices was first presented by Ghasemi et al. [2]. The authors investigated the effect of transverse magnetic field on the natural convection in a nanofluid filling a square enclosure and they studied the effects of appropriate parameters such as Rayleigh number, Hartmann number and solid fraction on the heat transfer performance of the enclosure. They found that the heat transfer rate increases with an increase of Rayleigh number but decreases with an increase of Hartmann number. Depending on the values of Hartmann number and Rayleigh number, an increase of the solid volume fraction may result in enhancement or deterioration of heat transfer performance. Aminossadati et al. [3] examined numerically the laminar forced convection of a water-Al_2O_3 nanofluid flowing through a horizontal micro-channel. The middle section of the micro-channel is heated with a constant and uniform heat flux and influenced by a transverse uniform magnetic field. The effects of the Reynolds number, the solid volume fraction and the Hartmann

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number on the flow and temperature fields and the heat transfer performance of the micro-channel are examined against numerical predictions. The results show that the micro-channel performs better heat transfers at higher values of Reynolds and Hartmann numbers. For all values of the Reynolds and Hartmann numbers considered in this study, the average Nusselt number on the middle section surface of the micro-channel increases as the solid volume fraction increases. The rate of this increase is considerably more higher values of the Reynolds number and at lower values of Hartmann number. Teamah and Al-Maghlany [4] numerically studied the natural convection in a square cavity filled with different nanofluids in the presence of magnetic field. They found that the addition of nanoparticles is necessary to enhance the heat transfer for weak magnetic field applications, but for strong magnetic field applications, there is no need for nanoparticles because the heat transfer will decrease. Kefayati et al. [5] investigated numerically MHD mixed convection in a lid-driven square cavity with linearly heated wall. It was demonstrated that the augmentation of Richardson number causes heat transfer to increase, as the heat transfer decreases by the increment of Hartmann number for various Richardson numbers and the directions of the magnetic field. Mahmoudi et al. [6] investigated numerically the entropy generation and enhancement of heat transfer in natural convection flow and heat transfer using copper Cu-water nanofluid in the presence of a constant magnetic field. The analysis uses a two-dimensional trapezoidal enclosure with the left vertical wall and inclined walls kept in a low constant temperature and a heat source with constant heat flux placed on the bottom wall of the enclosure. Their results show that at $Ra=10^4$ and 10^5 the enhancement of the Nusselt number due to the presence of nanoparticles increases with the Hartmann number, but at higher Rayleigh number, a reduction has been observed. In addition, it was observed that the entropy generation decreases when the nanoparticles are present, while the magnetic field generally increases the magnitude of the entropy generation. Ashorynejad et al. [7] investigated flow and heat transfer of a nanofluid over a stretching cylinder in the presence of magnetic field. Different types of nanoparticles as copper (Cu), silver (Ag), alumina (Al_2O_3) and titanium oxide (TiO_2) with water as their base fluid has been considered. They found that the Nusselt number increases as each of Reynolds number or nanoparticles volume fraction increase, but it decreases as magnetic parameter increase. In addition, it can be found that choosing copper (for small of magnetic parameter) and alumina (for large values of magnetic parameter) leads to the highest cooling performance for this problem. Reza Ashorynejad et al. [8] investigated numerically the effect of static radial magnetic field on natural convection heat transfer in a horizontal cylindrical annulus enclosure filled with nanofluid. The inner and the outer cylinder surfaces are maintained at the different uniform temperatures. The results reveal that the flow oscillations can be suppressed effectively by imposing an external radial magnetic field. Also, it is found that the average Nusselt number is an increasing function of nanoparticle volume fraction and Rayleigh number, while it is a decreasing function of Hartmann number. Malvani and Ganji [9] examined the laminar flow and convective heat transfer of alumina-water nanofluid inside a circular microchannel in the presence of a uniform magnetic field. They found that the ratio of the Brownian thermophoretic diffusivities has relatively significant effects on both distribution of nanoparticles and the convective heat transfer coefficient of nanofluids. It was further observed that for smaller nanoparticles, the nanoparticle volume fraction is uniform and abnormal variations in the heat transfer rate vanish. Moreover, in the presence of the magnetic field, the near wall velocity gradients increase, enhancing the slip velocity and thus the heat transfer rate and pressure drop increase. Salari et al. [10] solved the problem of entropy generation induced by natural convection of the Cu-water nanofluid in rectangular cavities with different circular angles and different aspect ratios. The authors showed that the Nusselt number increases with increasing Rayleigh number and solid volume fraction. Ben Hamida et al. [11] studied numerically natural convection heat transfer in an enclosure filled with an ethylene glycol-copper nanofluid under magnetic fields. They found that the effects of Hartmann number on dimensionless y-velocity are more significant at Rayleigh number $Ra=10^5$. For Hartmann numbers greater than 20, average Nusselt number decrease when the solid volume fraction increases. Afrand et al. [12] analyzed natural convection with an induced electric field in a vertical cylindrical annulus filled with liquid potassium. The flow is axisymmetric without a magnetic field, but asymmetrical when the magnetic field is oriented horizontally. Chamkha et al. [13] numerically studied entropy generation and natural convection in C-shaped cavity filled with CuO-water nanofluid under to a uniform magnetic field. They observed that the nanoparticles volume fraction enhances the natural convection, but undesirably increases the entropy generation rate. Esfandiary et al. [14] studied numerically the effects of inclination angle on natural convective heat transfer and fluid flow in an enclosure filled with Al2O3–water nanofluid. They demonstrated that the slip velocity mechanisms have caused the decreasing Nusselt number with increasing volume fraction of nanoparticles. Rashidi et al. [15] performed a numerical study of heat transfer of nanofluid flow in a vertical channel with sinusoidal walls under magnetic field. The results reveal that the average Nusselt number increases by increasing the Grashof number with various values of solid volume fractions. M. Battira and R. Bessaih [16] studied numerically the radial and axial magnetic fields effects on natural convection in an Al_2O_3 nanofluid filled vertical cylinder having an aspect ratio $H/R_0=1$, for two values of Rayleigh number ($Ra=10^3$ and $Ra=10^4$). The results indicate that for small values of the Hartmann number the average Nusselt number decreases when increasing the solid volume fraction and this decrease is more important if the magnetic field is applied in the axial direction and by increasing the Hartmann numbers. Sheikholeslami and Bhatti [17] analyzed numerically forced convective heat transfer in a porous semi-annulus in presence of uniform magnetic field. The results indicate that Nusselt number enhances with increase of nanofluid volume fraction, Darcy and Reynolds number while it reduces with increase of Lorentz forces. Sheikholeslami et al. [18] numerically studied nanofluid forced convection heat transfer in existence of magnetic field. They observed that velocity of nanofluid augments with rise of Reynolds number and Al_2O_3 volume fraction but it reduces with increase of Hartmann number. Convection mode reduces with enhance of Lorentz forces. Temperature gradient over the moving wall augments with augment of hot surface velocity and Al_2O_3 volume fraction. Yadollahi et al. [19] investigated the effects of magnetic field on free convection regime of silver-water nanofluid. The considered geometry is an F-shaped cavity under the influence of a constant magnetic field. They concluded that the increase in Hartman number causes a decrease in vertical velocity and heat transfer. By increasing Rayleigh number, the influence of Hartman number will be increased. An increase in dimensional ratio of the cavity causes a decrease in Nusselt number except in AR=0.4. Marina Astanina et al. [20] analyzed numerically natural convection combined with entropy generation of Fe_3O_4–water nanofluid within an open trapezoidal cavity filled with a porous layer and a ferrofluid layer under the effect of uniform inclined magnetic field. It has been found that an increase in Hartmann number leads to a growth of oscillations amplitude for average Nusselt number and average entropy generation. At the same time inclination angle $\alpha = \pi/2$ illustrates unstable behavior of heat and fluid flow. Sheikholeslami et al. [21] investigated H_2O based nanofluid magnetohydrodynamic free convection in a porous cubic cavity with hot sphere obstacle by means of Lattice Boltzmann method. Influences of Darcy number, Hartmann number, and Rayleigh number on Al_2O_3-H2O nanofluid treatment is demonstrated. The Results indicate that Lorentz forces makes temperature gradient to decrease. Thermal boundary layer becomes thicker with the increase of Hartmann number but opposite treatment is observed for Darcy number. Sheikholeslami et al. [22] investigated analytically uniform magnetic field impact on nanofluid flow between two circular cylinders using AGM. Results indicate that velocity reduces with augment of Lorentz forces but it rises with augment of Reynolds number. Temperature gradient enhances with rise of Hartmann number but it decreases with augment of other parameters. Dogonchi and Hashim [23] investigated the role of natural convection and thermal radiation on thermo-hydrodynamics of nanofluid heat transfer in an annulus between a wavy circular cylinder and a rhombus enclosure subject to a uniform magnetic field. They found that the local heat transfer rate decreases with an increase in aspect ratio in the absence of Hartmann number. In addition, for decreasing values of aspect ratio, the space for fluid flow inside enclosure becomes wider.

To the best knowledge of the authors, no attempts have been made yet to study the effects of magnetic field direction and strength and the nanoparticles concentration on heat transfer in vertical cylinder filled with CuO-Water nanofluid and having an aspect ratio $H/R_0 = 3$. The main objective of this study is a numerical investigation of the effect of magnetic field direction and various parameters such as Hartmann number, Rayleigh number, and nanoparticles concentration on the natural convection heat transfer of CuO-Water nanofluid in a vertical cylinder.

PROBLEM DESCRIPTION AND GOVERNING EQUATIONS

Problem description

The configuration is illustrated in Figure 1. A cylindrical enclosure having an aspect ration $H/R_0 = 3$ and filled with CuO-Water nanofluid. The bottom and top walls are maintained at hot (T_h) and cold (T_c) temperatures, respectively, while the sidewall of cylinder is adiabatic. It is assumed that the nanofluid is Newtonian and incompressible and the nanoparticles of CuO have uniform size and in thermal equilibrium with water. Two different external magnetic fields either in the radial (B_r) or axial (B_z) directions are applied. In addition, we assume that the induced magnetic field is negligible, because the magnetic Reynolds number is very less than one ($Re_m \ll 1$).

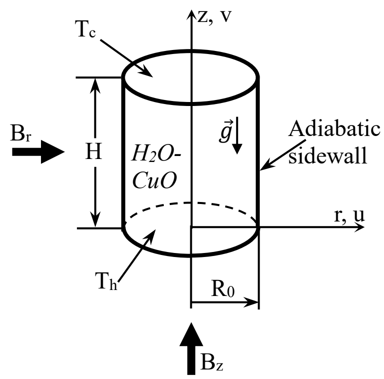


Figure 1. A schematic of the problem and boundary conditions.

By neglecting the dissipation and Joule heating and introducing the dimensionless parameters defined as follows:

$$R = \frac{r}{R_0}, \quad Z = \frac{z}{R_0}, \quad U = \frac{u}{(\alpha_f/R_0)}, \quad V = \frac{v}{(\alpha_f/R_0)}, \quad P = \frac{\bar{p}{R_0}^2}{\rho_{nf}{\alpha_f}^2}, \quad \theta = \frac{T-T_c}{T_h-T_c},$$

$$Ra = \frac{g\,\beta_f {R_0}^3(T_h-T_c)}{\nu_f\alpha_f}, \qquad Ha = B_0R_0\sqrt{\frac{\sigma_{nf}}{\rho_{nf}\nu_f}}, \qquad Pr = \frac{\nu_f}{\alpha_f}$$

The dimensionless governing equations for steady and two-dimensional axisymetic flow, with constant thermophysical properties, except in buoyancy force (Boussinesq approximation) are:

- Continuity equation:

$$\frac{\partial U}{\partial R} + \frac{\partial V}{\partial Z} = 0 \tag{1}$$

- Radial magnetic field:

- R - Momentum equation:

$$U\frac{\partial U}{\partial R} + V\frac{\partial U}{\partial Z} = -\frac{\partial P}{\partial R} + \frac{\mu_{nf}}{\rho_{nf}\rho_f}\left[\frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial U}{\partial R}\right) + \frac{\partial^2 U}{\partial Z^2}\right] - Ha^2\,\mathrm{Pr}\,U \tag{2}$$

- Z - Momentum equation:

$$U\frac{\partial V}{\partial R}+V\frac{\partial V}{\partial Z}=-\frac{\partial P}{\partial Z}+\frac{\mu_{nf}}{\rho_{nf}\rho_f}\left[\frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial V}{\partial R}\right)+\frac{\partial^2 V}{\partial Z^2}\right]+\frac{(\rho\beta)_{nf}}{\rho_{nf}\beta_f}\,Ra\,\mathrm{Pr}\,\theta \quad (3)$$

- Axial magnetic field:

- R - Momentum equation:

$$U\frac{\partial U}{\partial R}+V\frac{\partial U}{\partial Z}=-\frac{\partial P}{\partial R}+\frac{\mu_{nf}}{\rho_{nf}\rho_f}\left[\frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial U}{\partial R}\right)+\frac{\partial^2 U}{\partial Z^2}\right] \quad (4)$$

- Z - Momentum equation:

$$U\frac{\partial V}{\partial R}+V\frac{\partial V}{\partial Z}=-\frac{\partial P}{\partial Z}+\frac{\mu_{nf}}{\rho_{nf}\rho_f}\left[\frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial V}{\partial R}\right)+\frac{\partial^2 V}{\partial Z^2}\right]+\frac{(\rho\beta)_{nf}}{\rho_{nf}\beta_f}\,Ra\,\mathrm{Pr}\,\theta-Ha^2\,\mathrm{Pr}\,V \quad (5)$$

- Energy equation:

$$U\frac{\partial \theta}{\partial R}+V\frac{\partial \theta}{\partial Z}=\frac{\alpha_{nf}}{\alpha_f}\left[\frac{\partial^2 \theta}{\partial R^2}+\frac{\partial^2 \theta}{\partial Z^2}\right] \quad (6)$$

The effective density, the thermal diffusivity, the electrical conductivity, the heat capacitance and the thermal expansion of the nanofluid are defined respectively as:

$$\rho_{nf}=(1-\phi)\rho_f+\phi\,\rho_p \quad (7)$$

$$\alpha_{nf}=k_{nf}/(\rho C_p)_{nf} \quad (8)$$

$$\sigma_{nf}=(1-\phi)\sigma_f+\phi\,\sigma_p \quad (9)$$

$$(\rho C_p)_{nf}=(1-\phi)(\rho C_p)_f+\phi(\rho C_p)_p \quad (10)$$

$$(\rho\beta)_{nf}=(1-\phi)(\rho\beta)_f+\phi(\rho\beta)_p \quad (11)$$

The effective dynamic viscosity of the nanofluid modeled by Brinkman [24]:

$$\mu_{nf}=\frac{\mu_f}{(1-\phi)^{2.5}} \quad (12)$$

The thermal conductivity of the nanofluid proposed by Maxwell [25]:

$$k_{nf}=k_f\left[\frac{(k_p+2k_f)-2\phi(k_f-k_p)}{(k_p+2k_f)+\phi(k_f-k_p)}\right] \quad (13)$$

The dimensionless boundary conditions for velocity and temperature are:

Symmetry axe:

$$At\quad R=0,\qquad U=\frac{\partial V}{\partial R}=0,\qquad \frac{\partial\theta}{\partial R}=0 \quad (14a)$$

Adiabatic lateral wall:

$$At\quad R=1,\qquad U=V=0,\qquad \frac{\partial\theta}{\partial R}=0 \quad (14b)$$

Hot bottom disk:

$$At\quad Z=0,\qquad U=V=0,\qquad \theta=1 \quad (14c)$$

Cold top disk:

$$At \quad Z = \frac{H}{R_0}, \qquad U = V = 0, \qquad \theta = 0 \tag{14d}$$

The local Nusselt number on the top cold disk is defined by:

$$Nu_R(R) = -\frac{k_{nf}}{k_f}\left(\frac{\partial\theta}{\partial Z}\right)_{Z=H/R_0} \tag{15}$$

The average Nusselt number (Nu_m) is determined by integrating the local Nusselt along the cold disk:

$$Nu_m = \int_0^1 Nu_R(R)\, dR \tag{16}$$

NUMERICAL PROCEDURE AND VALIDATION

The numerical simulation of the considered problem was implemented in a FORTRAN language. The dimensionless equations (1) – (6) with the associated boundary conditions (14) are solved by the second-order accurate central differencing scheme and the SIMPLER algorithm [25]. The convergence U, V and θ was obtained when the maximum difference between two consecutive iterations is less than 10^{-5}.

Effect of mesh on the numerical solution

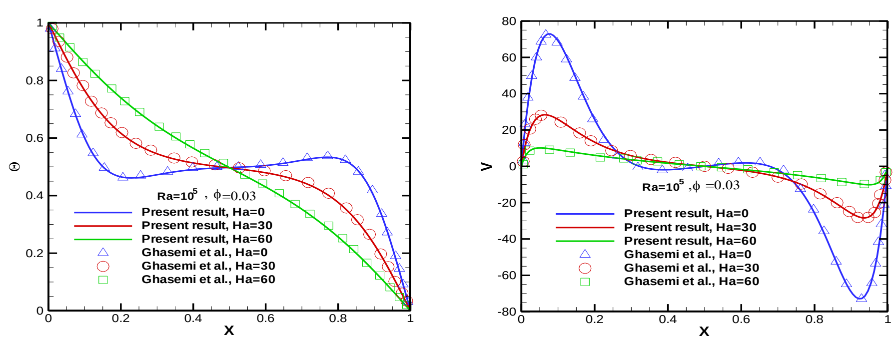
Six non-uniform grids are used (30×90), (40×120), (50×150), (70×210), (90×270) and (110×330) nodes. The variation of Nu_m with grid size at Ha = 5 (B_z), $\phi = 0.05$ and $Ra = 5 \times 10^3$ is illustrated in Table 1. It is clear that the grid independence is satisfied for (90×270) and (110×330). The grid (90×270) is adopted for all numerical simulations, in order to optimize the CPU time and the cost computations.

Grid	(30×90)	(40×120)	(50×150)	(70×210)	(90×270)	(110×330)
Nu_m	0.5215	0.4991	0.4910	0.4883	0.4882	0.4882

Table 1. Result of grid independence for $\emptyset = 0.05$,
$Ra = 5 \times 10^3$, Ha = 5 (B_z)

Validation of the Computer code

The results of our numerical simulations have been compared with the numerical results of Ghasemi et al. [2]. Figure 2 shows the dimensionless temperature (Figure 2(a)) and y-velocity (Figure 2(b)) along the horizontal mid-span of enclosure for $Ra = 10^5$ and $\emptyset = 0.03$ for three values of Ha (Ha=0, Ha=30 and Ha=60). It can be seen, that the present results reveal a very good agreement.



(a) 6 (b)

Figure 2. Validation of the results of the present study with results of
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RESULTS AND DISCUSSION

In this work, numerical examination has been accomplished to study the impacts of magnetic field direction (axial (B_Z) and radial (B_r)) and concentration of nanoparticles ($\emptyset = 0, 0.25, 0.05, 0.075, 0.1$) on the natural convection of CuO-water nanofluid in a vertical cylindrical enclosure. The impacts of the controlling parameters such as Rayleigh number($Ra = 10^3, 5 \times 10^3, 10^4$), Hartmann number ($Ha = 0 - 60$) are also considered.

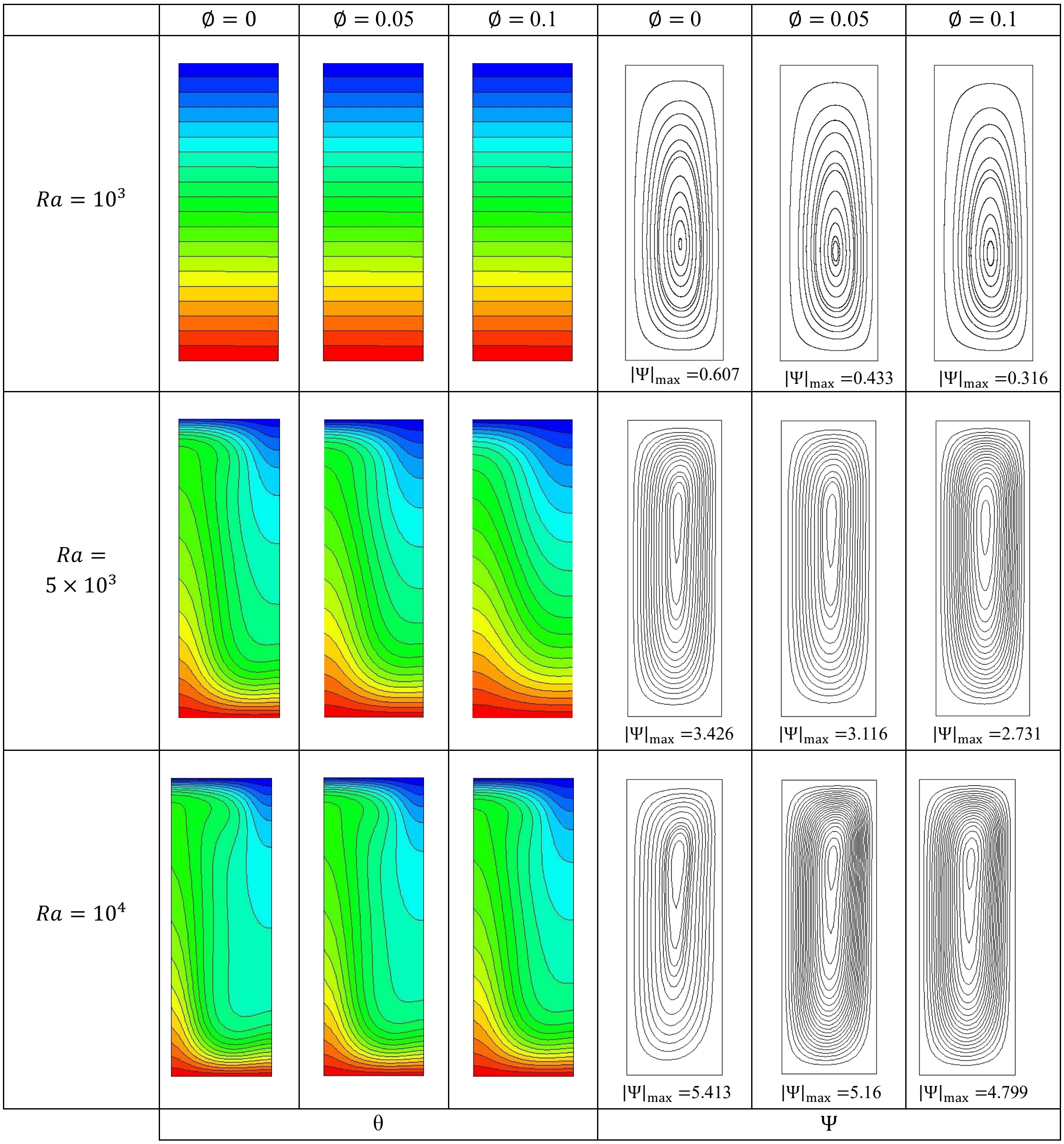

Figure 3. Variation of isotherms (θ) and streamlines (Ψ) with nanoparticles volume fraction (∅) for three values of Rayleigh number without application of magnetic field (Ha=0)

The effect of the increase of the nanoparticles volume fraction without application of magnetic field (Ha = 0), on the isotherms and on the streamlines, is represented in figure 3, for the three Rayleigh values. It is clear that, in this case and for the low value of Rayleigh number $Ra = 10^3$, the low buoyancy force intensity generates a weak flow. The isotherms uniformly distributed inside the cylinder show the dominance of the conductive regime on the heat transfer. As the Rayleigh number increases, the buoyancy force becomes more important; the isotherms become tighter near both hot and cold disks. Also, it is clear that the strength of circulation $|\Psi|_{max}$ decreases by adding the nanoparticles volume fraction and increases with Rayleigh number.

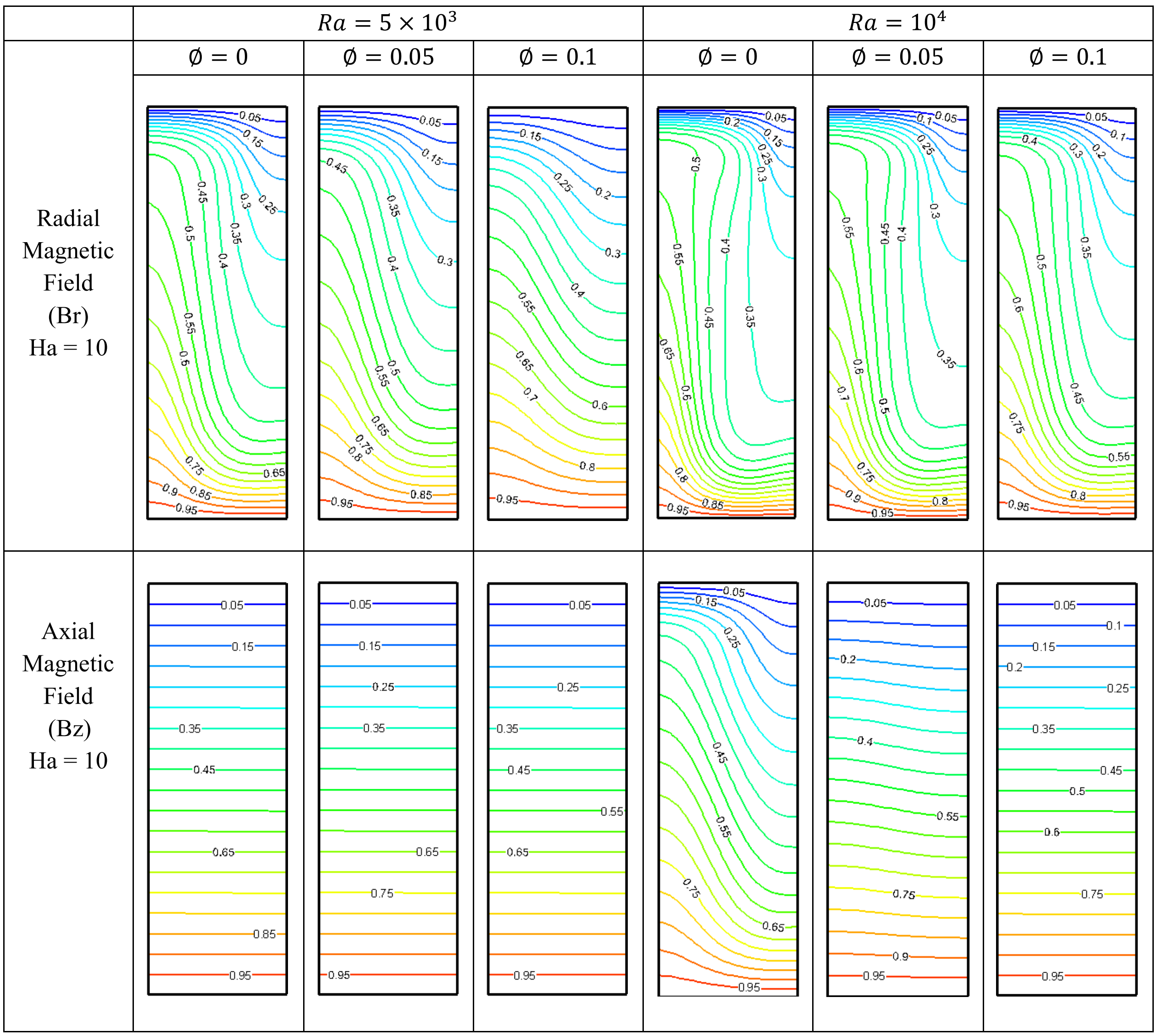

Figure 4. Isotherms for Ha=10 for two magnetic field directions (axial and radial) for two values of Rayleigh number.

Figure 4 presents isotherms when a magnetic field (Ha =10) is applied once in axial direction and a second time in radial one and this for $Ra = 5 \times 10^3$ and $Ra = 10^4$. For $Ra = 5 \times 10^3$ the conduction dominates completely when the field is axially directed for all values of volume fraction nanoparticles but for $Ra = 10^4$ the conduction dominance starts at this value of Ha but only with $\emptyset = 0.1$. In the case where the magnetic field is radially applied, always convection dominates. The effects of magnetic field direction on the isotherms and streamlines are also illustrated in figure 5. The buoyancy-driven circulating flows within the cylinder are evident for both values of Hartmann number. The conductive regime dominates from Ha = 5 and $\emptyset = 0.1$ when the magnetic field is axial. However, if the magnetic field is radial the conduction dominance starts for Ha = 20 and $\emptyset = 0.1$.

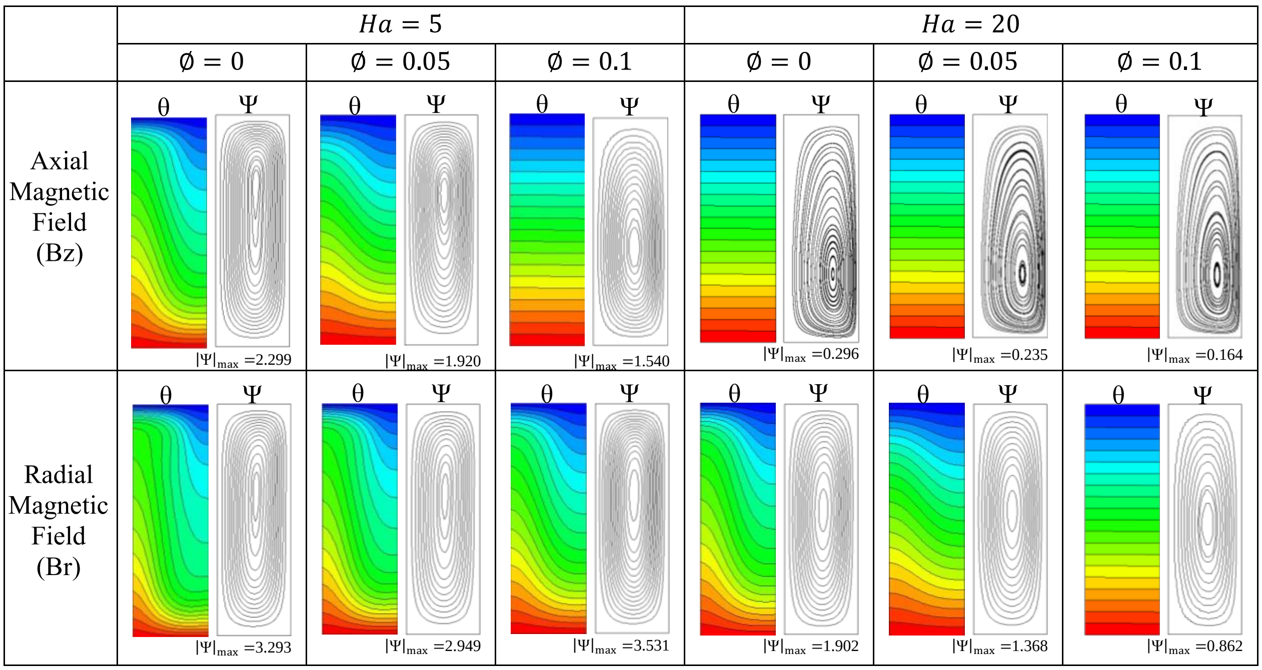

Figure 5. isotherms (θ) and streamlines (Ψ) for Ha =5 and Ha=10 in two magnetic field directions and for three values nanoparticles volume fraction (∅) at $Ra = 5 \times 10^3$

ϕ		Ha=0	Ha=5		Ha=10		Ha=20		Ha=40	
			B_z	B_r	B_z	B_r	B_z	B_r	B_z	B_r
0	**Nu_m**	1.6039	1.3931	1.5796	0.6672	1.4934	0.3318	1.1883	0.3162	0.5141
	$\lvert\Psi\rvert_{max}$	5.414	3.893	5.287	2.304	4.890	0.768	3.622	0.166	1.496
0.05	**Nu_m**	1.6726	1.2607	1.6210	0.3850	1.4766	0.3829	1.0486	0.3649	0.3823
	$\lvert\Psi\rvert_{max}$	5.160	3.524	5.008	1.878	4.544	0.518	3.126	0.123	0.903
0.1	**Nu_m**	1.6427	1.0026	1.5669	0.4394	1.3700	0.4394	0.8516	0.4189	0.4394
	$\lvert\Psi\rvert_{max}$	4.799	3.117	4.617	1.483	4.094	0.375	2.559	0.0975	0.514

Table 2. Variation of the Average Nusselt number (Nu_m) and the maximum stream function $|\Psi|_{max}$ with the solid volume fraction at various Hartmann number for both magnetic field directions at $Ra = 10^4$.

Table 2. illustrates the variation of the average Nusselt number (Nu_m) and the maximum stream function with the solid volume fraction of nanoparticles at different values of Hartmann number for both magnetic field directions radial and axial for $Ra = 10^4$. Values show that the solid volume fraction of nanoparticles in the base fluid has a significant influence on the performance of heat transfer in the cylindrical enclosure at all Hartmann number values. It is clear that the number of Nusselt decreases sharply with the increasing number of Hartmann, especially when the magnetic field is applied in the axial direction. As the number of Nusselt describes the intensity of convection heat transfer, this observation clearly indicates the significant suppression of convection heat transfer by the magnetic field. For all Hartmann number values, if the solid volume fraction increases $|\mathbf{\Psi}|_{\mathbf{max}}$ is reduced, the addition of solid nanoparticles to the base fluid implies an increase of μ_{nf}/ρ_{nf} in the diffusive term. This means a lower flow strength and lower values of maximum stream function.

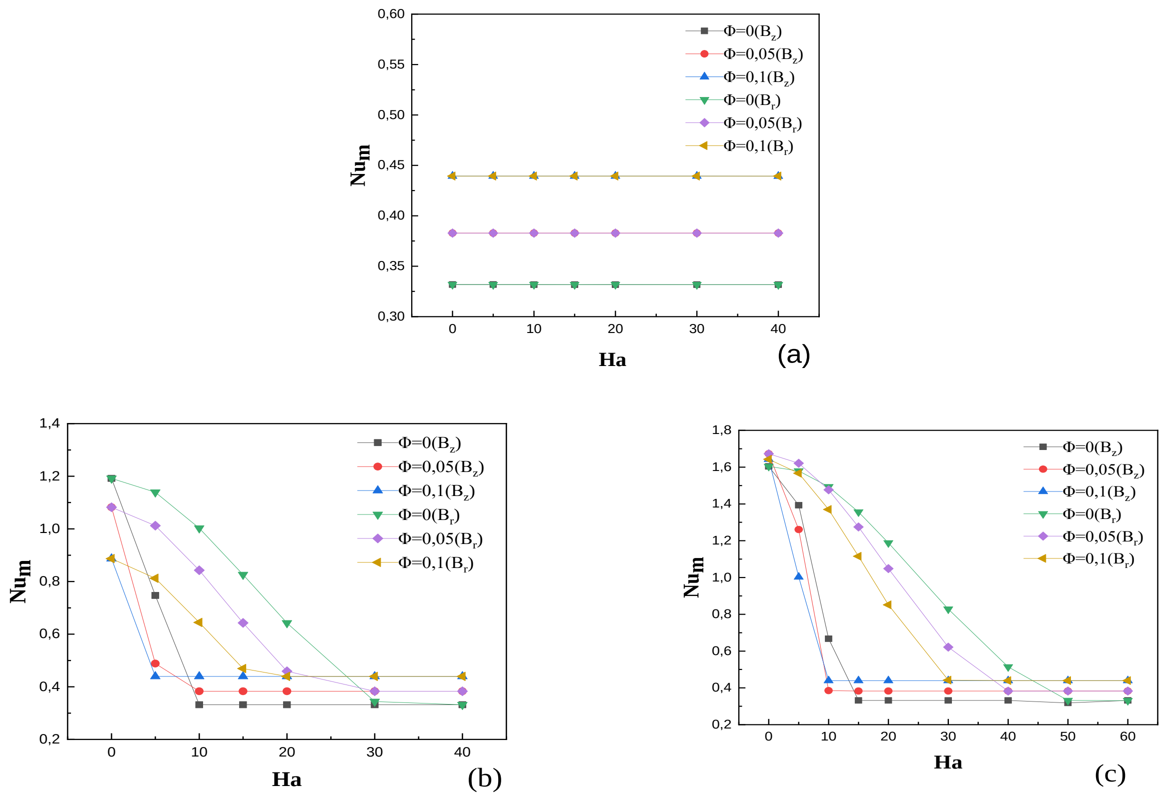

Figure 6. Variation of the Average Nusselt number (Nu_m) along the cold disk with Hartmann number for (a) $Ra = 10^3$ (b) $Ra = 5 \times 10^3$ (c) $Ra = 10^4$ and for three values of the solid volume fraction ($\emptyset$) for both magnetic field directions.

Figures 6 (a), (b) and (c) show the effect of the Hartmann number for both directions of the magnetic field on the variation of the average Nusselt number for three values of $\emptyset$ and for $Ra = 10^3$, $Ra = 5 \times 10^3$ and $Ra = 10^4$ respectively. For $Ra = 10^3$ (Figure 6 (a)) where the conductive thermal transfer remains dominant, neither the intensity of the magnetic field nor its direction have significant effects on the heat transfer performance, but the increase in the volume fraction of the nanoparticles significantly increases this performance. For $Ra = 5 \times 10^3$ and $Ra = 10^4$, Figures 6. (b) and 6. (c) respectively show that for the radial direction of the magnetic field (Br), the performance of the heat transfer decreases by increasing the intensity of the magnetic field (Ha) and also decreases with the increase of nanoparticles volume fraction ($\emptyset$), but this before Ha exceeds the value of 30 for $Ra = 5 \times 10^3$ and the value of

50 for $Ra = 10^4$. Beyond these two values of the number of Ha, the value of the Nusselt remains unchanged with the increase of the intensity of the magnetic field, but decreases with the increase of the solid volume fraction in the nanofluid. For the case where the magnetic field is directed axially (Bz), the average Nusselt number decreases with the increase of the volume fraction of the nanoparticles for Ha ≤ 10 for $Ra = 5 \times 10^3$and for Ha ≤ 15 for $Ra = 10^4$. It is also clear that its reduction with the increase of the intensity of the magnetic field is greater compared to the case where the magnetic field is radial. When Ha exceeds the value of 10 for $Ra = 5 \times 10^3$ and the value of 15 for $Ra = 10^4$, the heat transfer performance seems invariable with the increase of Ha but increases with the increase of nanoparticle volume fraction in the nanofluid ($\emptyset$) .

CONCLUSION

In this work, we numerically analyzed the effects of magnetic field strength and direction, concentration of nanoparticles on natural convection in a cylindrical cavity filled with water-CuO nanofluid for three values of Rayleigh number. The cylindrical cavity is subjected to an external magnetic field applied once axially (Bz) and a second time radially (Br).

The main results are:
The magnetic field reduces the circulation in the cylindrical cavity.
The increase in the intensity of the magnetic field increases the size of the Lorentz forces, and consequently the strength of circulation decreases and this decrease is more pronounced when the magnetic field is directed axially.
When the conducting regime is dominant (Ra = 103), the intensity and the direction of the magnetic field have a small effect on the heat transfer rate, but the increase in the volume fraction of the nanoparticles considerably increases the heat transfer performance for all the values of Ha.
For Ra = 5.103 and Ra = 104, where the convective mode dominates, the increase in the volume fraction of the nanoparticles decreases the heat transfer performance when the magnetic field is radial and also when the magnetic field is axial but for the low values of Hartmann (Ha≤10), beyond this value of Ha the heat transfer performance increases with the increase of the volume fraction of the nanoparticles.

NOMENCLATURE

B_0	Magnetic field, Tesla
C_p	Specific heat, J kg^{-1} K^{-1}
g	Gravitational acceleration, m s^{-2}
H	Cylinder height, m
Ha	Hartmann number
k	Thermal conductivity, W m^{-1} K^{-1}
Nu_m	Average Nusselt number
Nu_R	Local Nusselt number on the top cold disk
p	Fluid pressure, Pa
P	Dimensionless pressure
$\bar{p}$	Modified pressure, Pa
Pr	Prandtl number
r, z	Cylindrical coordinates, m
R, Z	Dimensionless coordinates
Ra	Rayleigh number
R_0	Cylinder radius, m
T	Temperature, K
u, v	Radial, Axial velocities, m s^{-1}
U, V	Dimensionless Radial, Axial velocities, m s^{-1}

Greek symbols

α	Thermal diffusivity, m^2 s^{-1}
β	Thermal expansion coefficient, K^{-1}
$\emptyset$	Solid volume fracyion
μ	Dynamic viscosity, kg^{-1} m^{-1} s^{-1}
ν	Kinematic viscosity, m^2 s^{-1}
θ	Dimensionless temperature $(T - T_c)/(T_h - T_c)$
ρ	Density, kg m^{-3}
σ	Electrical conductivity, μS cm^{-1}
ψ	Dimensionless stream function

Subscripts

c	Cold
h	Hot
f	Fluid (pure water)
nf	Nanofluid
p	Nanoparticle
r, z	Radial, axial directions

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