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Effect of Magnetic Field on Heat Transfer of Nanofluid with Variable Properties on the Inclined Enclosure

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The purpose of this study is to investigate the effect of magnetic field on the fluid flow and natural convection of CuO-water nanofluids with variable properties in an inclined square enclosure. The horizontal walls of cavity are insulated, the left sidewall assumed as hot wall and the right sidewall assumed as cold wall. Effects of Rayleigh numbers 10^3, 10^4, 10^5 and 10^6, Hartmann numbers 0, 10, 50, with horizontal angles of cavity, 0°, 30° and 60°, and solid volume fraction of nanoparticles 0%, 2% and 4% are explored. Governing equations were solved numerically using finite volume and the SIMPLER algorithm. The result show that with applying magnetic field and increasing it, the velocity of nanofluids and thus the power of fluid decreases and behavior of nanofluids is more close to thermal conductivity than natural convection. At all ranges of studied Rayleigh numbers and volume fractions, with increasing the Hartmann number, the average Nusselt number decreases. Also with increasing cavity angle with the horizontal axis, the values of Nusselt number on the all ranges of Rayleigh numbers decreases.

Keywords: Nano-fluid, Natural convection, Magnetic field, Variable properties, Numerical solution

1 Introduction

Natural convection, due to the simplicity of the process, economical advantage, low noise and regain, has many applications in various branches of industry, such as refrigeration, air conditioning systems, electrical transformer devices and etc. also in a variety of industrial equipment such as electronic components, heat exchangers, solar collectors and such cases like these, natural convection is used. Always have access to the dimensions of the devices smaller, lighter and more efficient for better heat transfer in industrial equipment such as electronic components, heat exchangers, etc. is desirable. Since nanofluids have higher thermal conductivity than common fluids, in recent years have been considered. Abu-Nada et al. [1] studied on natural convection between two coaxial cylinders filled with nanofluids using the finite volume method. They investigated different nanofluids containing Cu, Ag,

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Al_2O_3 and TiO_2 nanoparticles were evaluated based on fluid water and its results are presented as curves of Nusselt number changes. They reported that at large Rayleigh numbers and aspect ratios, nanoparticles with higher thermal conductivity, causes more heat transfer. But at middling Rayleigh numbers, nanoparticles with low thermal conductivity reduce the rate of heat transfer. Arefmanesh et al. [2] investigated the natural convection heat transfer and fluid flow of water-TiO_2 nanofluids, into the space between two coaxial cavities with different aspect ratios and Rayleigh numbers. According to their results, the natural convective heat transfer coefficient in terms of the Rayleigh number increases with increasing volume fraction of nanoparticles and aspect ratios. Sheikhzadeh et al. [3] numerically studied the water-Cu nanofluids in a cavity with hot and cold vertical walls. Based on their results, the minimum average Nusselt number occurs when the local heating on the right and left walls of cavity applies on top and bottom, respectively. Fluid flow under the influence of a magnetic field in the cooling of the electronic systems which are under the influence of a magnetic field, cooling electrical transformers and etc. are discussed. Kandaswamy et al. [4] studied effect of magnetic field on the natural convection of the fluid in a cavity with thermal sources on the vertical sidewalls at different Rayleigh and Hartmann numbers. According to their results, the average Nusselt number decreases with increasing Hartmann number. Pirmohammadi and Ghasemi [5] studied numerically the effect of magnetic field on the natural convection of fluid in an inclined square cavity. Their results showed that the flow field and heat transfer are strongly dependent on the magnetic field and cavity's angle. Mahmoudi et al. [6] numerically investigated the effect of magnetic field on the natural convection of water-CuO nanofluids in a triangular enclosure. Based on their results, with increasing the magnetic field, the Nusselt number decreases. Ashorynejad et al [7] conducted a numerical study of the effect of magnetic field on the natural convection of water-Ag nanofluids in the space between two coaxial circular cavities. According their results, the average Nusselt number and the Rayleigh number increase with increasing volume fraction, but decrease with increasing Hartmann number.

To the best knowledge of authors, no studies that investigated the effect of magnetic field on the fluid flow and heat transfer of nanofluids with variable properties on the inclined square enclosure have been reported. In present study, fluid flow and heat transfer of water-CuO nanofluids natural convection in square enclosure with insulated horizontal walls and hot left wall and cold right wall, in various Rayleigh and Hartmann numbers and volume fraction of 0 to 4% of the nanoparticles is studied.

2 Governing equations and boundary conditions

The thermo-physical properties of water as a base fluid and nanoparticles of the CuO are presented in table 1 [8]. Solving geometry and boundary conditions are shown in figure (1). Horizontal walls of enclosure are insulated, the left sidewall assumed as hot wall (in temperature T_h) and the right sidewall assumed as cold wall (in temperature T_c). Dimensions of the enclosure assumed as L.

Table 1 Thermo-physical properties for base fluid and nanoparticles (300 K) [8]

	ρ (kg m^{-3})	c_p (J kg^{-1} K^{-1})	k (W m^{-1} K^{-1})	$\beta \times 10^5$ (K^{-1})
Water	997.1	4179	0.613	21
CuO	6320	535.6	76.5	1.8

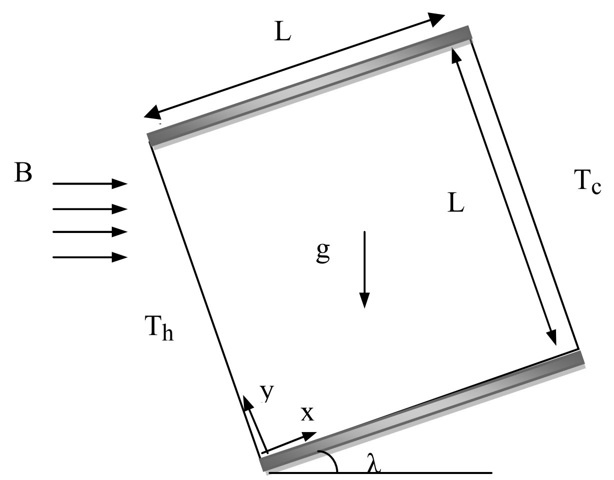

Figure 1 Schematic diagram and boundary conditions

Using the dimensionless variables (1), dimensionless equations including mass conservation (2), conservation of momentum along the x (3) and y (4) directions and energy conservation (5) for the two-dimensional, steady and laminar flow are:

$$X=\frac{x}{L},Y=\frac{y}{L},S=\frac{s}{L},U=\frac{uL}{\alpha_f},V=\frac{vL}{\alpha_f}$$
$$\theta=\frac{T-T_c}{T_H-T_c},P=\frac{pL^2}{\rho_{nf}\,\alpha_f{}^2},\mathrm{Ra}=\frac{\mathrm{g}\beta\Delta\mathrm{TL}^3}{\nu\alpha},\ \mathrm{Ha}=\mathrm{B}_0\,H\sqrt{\frac{\sigma_{nf}}{\rho_{nf}\,\upsilon_f}} \tag{1}$$

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{2}$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\frac{1}{\rho_{nf}\,\alpha_f}\frac{\partial}{\partial X}\left(\mu_{nf}\frac{\partial U}{\partial X}\right)+\frac{\partial}{\partial Y}\left(\mu_{nf}\frac{\partial U}{\partial Y}\right)+\frac{(\rho\beta)_{nf}}{\rho_{nf}\,\beta_f}Ra\Pr\theta\sin\lambda-\mathrm{Ha}^2\times\Pr\times U\sin\lambda \tag{3}$$

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\frac{1}{\rho_{nf}\,\alpha_f}[\frac{\partial}{\partial X}\left(\mu_{nf}\frac{\partial U}{\partial X}\right)+\frac{\partial}{\partial Y}\left(\mu_{nf}\frac{\partial U}{\partial Y}\right)]+\frac{(\rho\beta)_{nf}}{\rho_{nf}\,\beta_f}Ra\Pr\theta\cos\lambda-\mathrm{Ha}^2\times\Pr\times V\cos\lambda \tag{4}$$

$$U\frac{\partial\theta}{\partial X}+V\frac{\partial\theta}{\partial Y}=\frac{1}{\left(\rho c_p\right)_{nf}\alpha_f}[\frac{\partial}{\partial X}\left(k_{nf}\frac{\partial\theta}{\partial X}\right)+\frac{\partial}{\partial Y}\left(k_{nf}\frac{\partial\theta}{\partial Y}\right)] \tag{5}$$

λ is the angle of the cavity with horizontal axis. Magnetic field appears as a body force calling Lorentz force. Hartmann number is a measure of the Lorentz body force. Increasing the Hartmann number shows the magnetic field strength is increased. Due to the geometry, dimensionless boundary conditions are:

$$\begin{aligned} &U=V=0,\ \frac{\partial\theta}{\partial Y}=0 && \text{On the horizontal walls}\\ &U=0,V=0,\ \theta=0 && \text{On the right wall}\\ &U=0,V=0,\ \theta=1 && \text{On the left wall}\end{aligned} \tag{6}$$

Nanofluid characteristics as density, heat capacitance, thermal expansion coefficient, thermal diffusivity, static part of viscosity [9] and thermal conductivity [10] can be attained by equations (7) to (14), respectively:

$$\rho_{nf}=(1-\varphi)\rho_f+\varphi\rho_s \tag{7}$$

$$(\rho c_p)_{nf}=(1-\varphi)(\rho c_p)_f+\varphi(\rho c_p)_s \tag{8}$$

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

$$\alpha_{nf} = \frac{k_{nf}}{(\rho c_P)_{nf}} \tag{10}$$

$$\mu_{eff} = \mu_{Static} + \mu_{Brownian} \tag{11}$$

$$k_{eff} = k_{Static} + k_{Brownian} \tag{12}$$

$$\mu_{Static} = \mu_f (1-\varphi)^{-2.5} \tag{13}$$

$$k_{Static} = k_f \left[\frac{(k_s + 2k_f) - 2\varphi(k_f - k_s)}{(k_s + 2k_f) + \varphi(k_f - k_s)} \right] \tag{14}$$

Where $\mu_{Brownian}$ and $k_{Brownian}$ defined as [11]:

$$\mu_{Brownian} = 5\times10^4 \chi\varphi\rho_f \sqrt{\frac{\kappa T}{2\rho_s R_s}} \xi(T,\varphi) \tag{15}$$

$$k_{Brownian} = 5\times10^4 \chi\varphi\rho_f c_{p,f} \sqrt{\frac{\kappa T}{2\rho_s R_s}} \xi(T,\varphi) \tag{16}$$

ρ_s and R_s ($23.5\times10^{-9}\ m$) are density and radius of nanoparticles respectively and κ is Boltzmann constant $\left(\kappa = 1.3807\times10^{-23}\ J/K\right)$.For λ and ζ functions which experimentally estimated for $300 < T\,(K) < 325$, for water-CuO nanofluid are [11]:

$$\chi = 0.0137(100\varphi)^{-0.8229}\ for\ \ \varphi \le 1\% \ \ , \ \ \chi = 0.0011(100\varphi)^{-0.7272}\ for\ \ \varphi > 1\% \tag{17}$$

$$\xi(T,\varphi) = (-6.04\varphi + 0.4705)T + (1722.3\varphi - 134.63)\ for\ \ 1\% \le \varphi \le 4\% \tag{18}$$

The convective heat transfer coefficient is:

$$h_{nf} = \frac{q}{T_H - T_c} \tag{19}$$

The Nusselt number according to height of enclosure presented by:

$$\mathrm{Nu} = \frac{h_{nf}\mathrm{L}}{k_f} \tag{20}$$

The heat flux is:

$$q = -k_{nf}\frac{T_H - T_c}{\mathrm{L}}\left.\frac{\partial\theta}{\partial X}\right|_{X=0} \tag{21}$$

With replacing (19) and (21) into (20), the Nusselt number is:

$$\mathrm{Nu} = -\left(\frac{k_{nf}}{k_f}\right)\left.\frac{\partial\theta}{\partial X}\right|_{X=0} \tag{22}$$

And the average Nusselt number at hot wall is:

$$\mathrm{Nu}_{\mathrm{Avg}} = \frac{1}{L}\int_0^1 Nu\, dY \tag{23}$$

3 Numerical simulation

Governing equations are solved numerically using finite volume and SIMPLER method. In order to validate the results which obtained by computer program, a numerical simulation was carried out and its results compared with the results presented in the paper [2], in Table 2.

Table 2 Average Nusselt number in natural convection of wate-TiO_2 nanofluids

Arefmanesh et al. [2]	Present work	φ	Ra
1.42	1.40	0.02	10^4
2.51	2.48	0.04	10^5

In order to find an appropriate grid which led to the independence of resulte fron the grid, the average Nusselt number for water-CuO nanofluids for grid with different number of nodes obtained and compared in Table (3). Giving the average Nusselt number values, it seems that a 111×111 grid points is suitable.

Table 3 Average Nusselt number on the hot wall for water -CuO nanofluids (φ=0.04) at Ra=10^5. Ha=0, λ =0

nodes	71×71	91×91	111×111	131×131
Nu_{avg}	5.04	5.11	5.14	5.15

The convergence measure for pressure, velocity and temperature is obtained of equation (24), where M and N are the number of grid points in the x and y direction, respectively and ζ represents the resolved variable. k is the number of iterations and the maximum amount of error is 10^{-6}.

$$\text{Error}=\frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\left|\zeta_{i,j}^{k+1}-\zeta_{i,j}^{k}\right|}{\sum_{i=1}^{M}\sum_{j=1}^{N}\left|\zeta_{i,j}^{k+1}\right|}\leq10^{-6} \tag{24}$$

4 Results and discussion

4.1 Streamlines and isotherms

In figure (2) the streamlines and isotherms at φ=0.02, Ra=10^3 and 10^6, and different Hartmann numbers are shown. At $\lambda=0^\circ$ and Ra=10^3, with increasing the Hartmann number, the circular streamlines are more stretched in the vertical direction so that at Ha=50, this curve make it quite vertical. This behavior of streamlines is due to the effect of Lorentz force due to the magnetic field which applied along the vertical direction and down. This force causes suppression of natural convection of nanofluids and behavior of it, is closer to thermal conductivity. At Ra=10^6, buoyancy force and thus the natural convection of nanofluids compared with Ra=10^3 is higher and the flow field is stronger, therefore Lorentz force has lower effect on the behavior of the nanofluids. At $\lambda=30^\circ$ and $\lambda=60^\circ$ and Ra=10^3, behavior of streamlines is similar to case with $\lambda=0^\circ$ at this angles and Ra=10^6, with increasing the Hartmann number, the curvature of the streamlines reduces which indicate decreasing natural convection and approaching the behavior of nanofluids to thermal conductivity.

Isothermal lines at Ra=10^3 and all investigated angles have very little curvature, which represents weak natural convection at these Rayleigh numbers. At all investigated angles, with increasing the Hartmann number, the curvature of the isotherms also decreases and behavior of nanofluids approaches to thermal conductivity, so that at Ha=50, isotherms are perfectly vertical. At $\lambda = 0^\circ$ and Ra=10^6 and Ha=0 and 10, isotherms at the edges of the hot and cold walls are dense, and central space of the cavity is almost horizontal. At Ha=50, compactness of isothermal lines at the edges of the hot and cold walls are preserved, but at the central space of the cavity, isothermals are slightly inclined to the vertical direction. This behavior is induced because the Lorentz force acting on the fluid flow. At Ra=10^6 and $\lambda =$ 30° and $\lambda = 60^\circ$, isothermal lines at Ha=0 and 10, compared to Ha=50, are more curved. Reducing the curvature of lines shows a decrease in the natural convection of nanofluids. In fact, with increasing the Hartmann number and enhancing the Lorentz force, natural convection of nanofluids decreases and therma conductivity is dominant. Reviewing isothermals and streamlines in this section, as a general outcome we can say: with increasing the Hartmann number, natural convection of nanofluids reduces and behavior of nanofluids changes to thermal conductivity.

4.2 Nusselt number changes

In figure (3), the average Nusselt number in terms of the Hartmann number at various Rayleigh numbers and λ is shown. At all investigated angles and all Rayleigh numbers, Nusselt number decreases with an increase in Hartmann number. The reason for this behavior of Nusselt number is reducing the natural convection of nanofluids because of increasing Lorentz force due to the increasing magnetic field strength. At Ra=10^3, flow has no great power to move. Indeed, at this Rayleigh number, therma conductivity has major role in heat transfer and thus with increasing the Hartmann number, average Nusselt number has no supposable changes. This was expressed over that the impact of the magnetic field on the convection of nanofluids is reducing the power of motion.

As shown in figure (3), by an increase of λ, Nusselt number values decreases at all Rayleigh numbers. This behavior indicates with increasing the angle between cavity and horizontal axis, the power of motion of nanofluids due to the reducing the of the influence of buoyancy in the vertical direction force, decreases and as result heat transfer rate reduces.

In figure (4), changes of the average Nusselt number in terms of volume fraction at different Hartmann numbers and different angles for Ra=10^3 and 10^6 are shown. At $\lambda = 0^\circ$ and $\lambda = 60^\circ$, at all shown Hartmann and Rayleigh numbers, the average Nusselt number increases with increasing volume fraction of nanoparticles and thus increasing the thermal conductivity, heat transfer rate increases too. So the average Nusselt number, which is a measure of heat transfer increases too. In figure (4), it can be seen that at low Rayleigh numbers, such as 10^3, at Ha=10 and 50, changes in the Nusselt number are close together while at high Rayleigh numbers, su ch as 10^6, at Ha=0 and 10, changes in the Nusselt number are close together.

At low Rayleigh numbers, the convection of nanofluids is low and with increasing the Hartmann number, there is a deniable impact on the natural convection of nanofluids and thus on Nusselt number changes, but art larger Rayleigh numbers, with more convection of fluid, the effect of Lorentz force on natural convection of nanofluids is more and reduces the convection and thus reduces the heat transfer. As a result, at Ra=10^6 and Ha=0 and 10, the Lorentz force is not yet significant and changes in Nusselt number are close together.

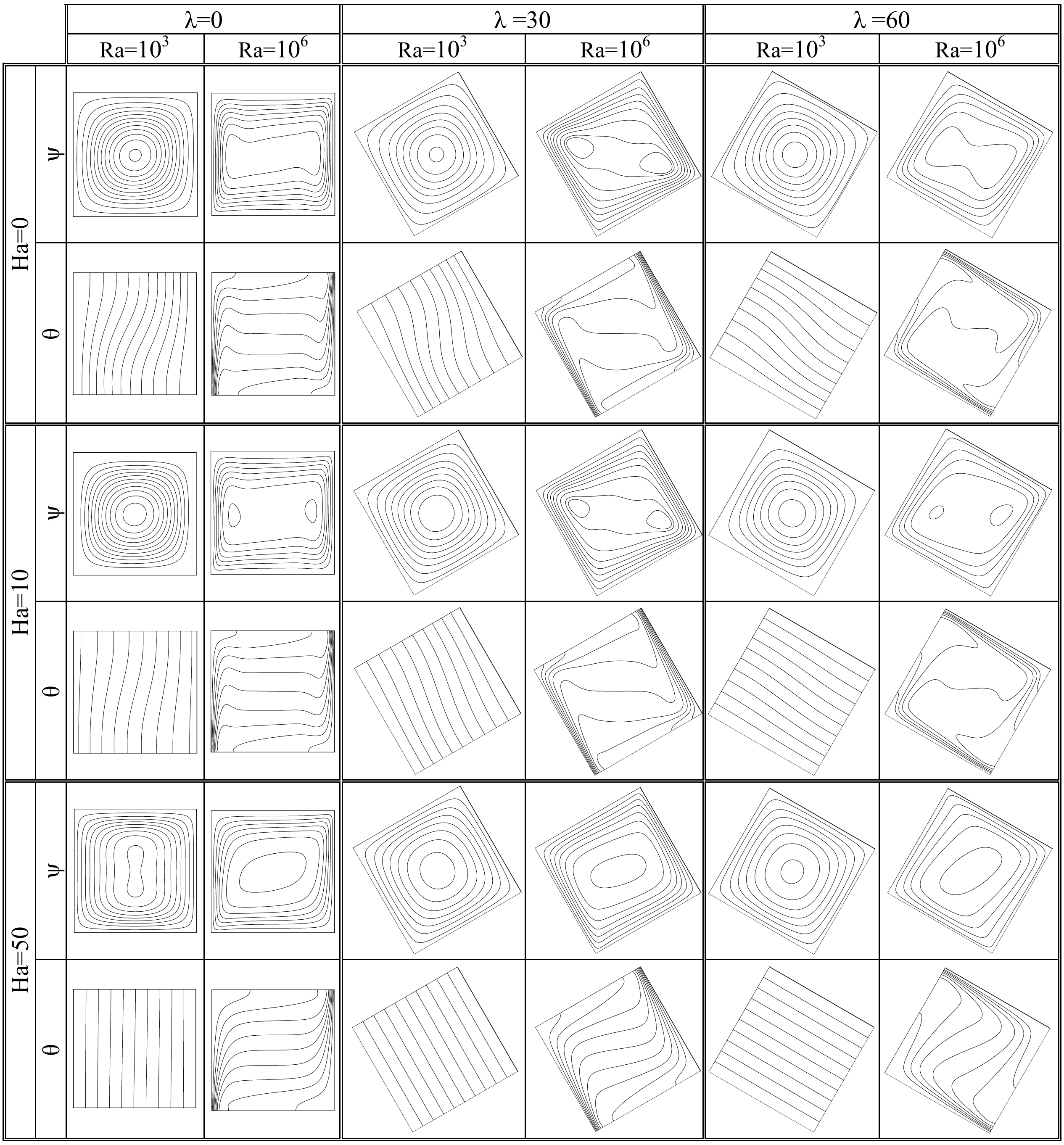

Figure 2 Streamlines and isotherms at φ=0.02, Ra=10^3 and 10^6, and different Hartmann numbers

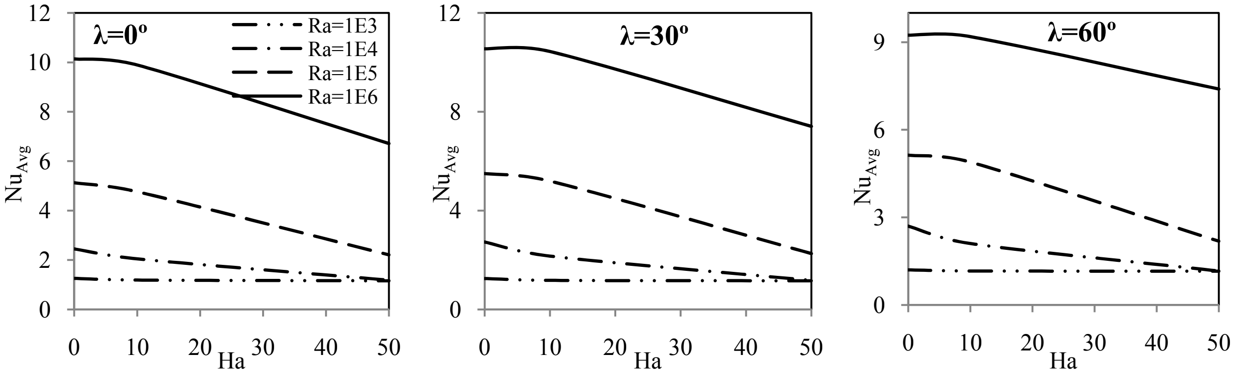

Figure 3 variation in the average Nusselt number versus Hartmann number at all Rayleigh numbers and all different angles between cavity and horizontal axis

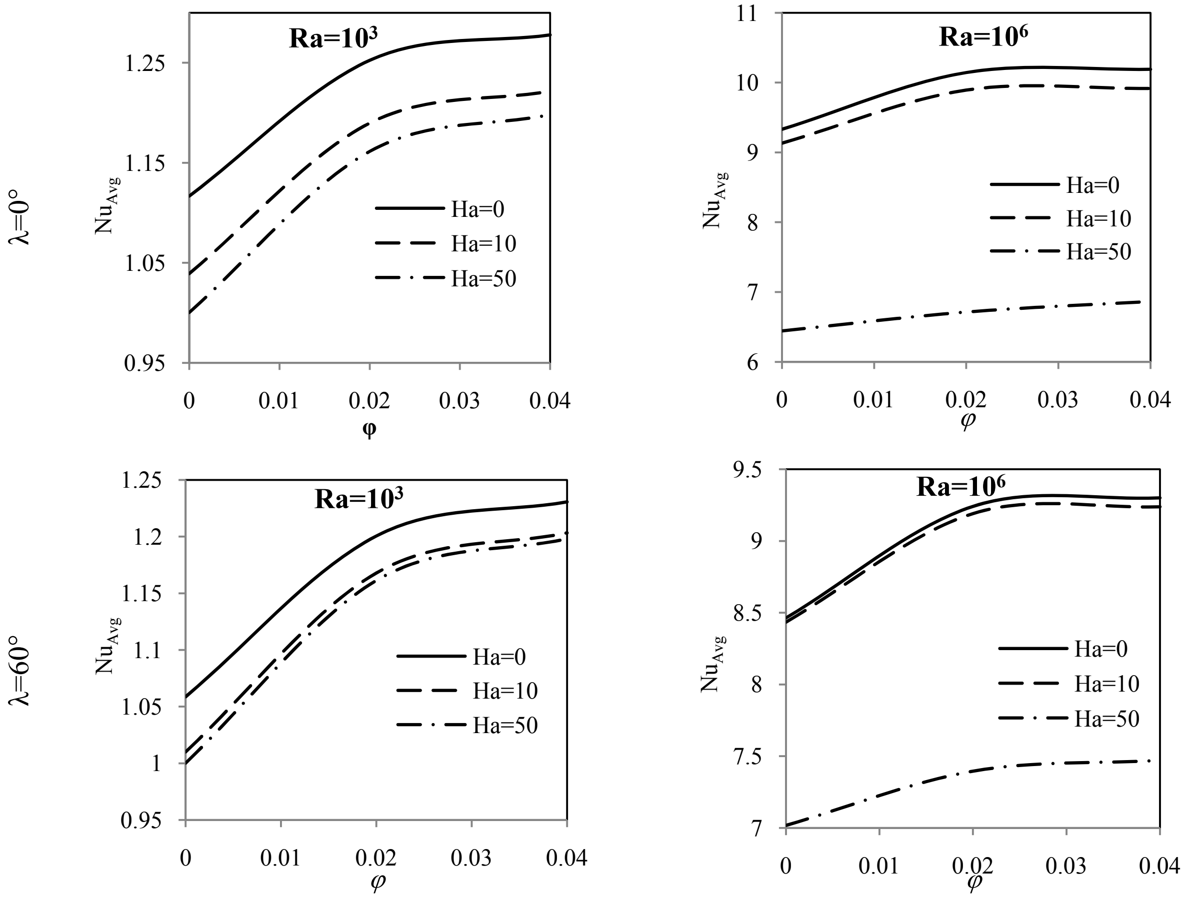

Figure 4 variation in the average Nusselt number interms of volume fraction at different Hartmann and Rayleigh numbers and different angles

5 Conclusions

In this study, the effect of magnetic field on the flow field and natural convection heat transfer of water-CuO nanofluids with variable properties for an inclined enclosure was investigated. The horizontal walls are insulated, the right sidewall is cold wall and the left sidewall is hot. Study carried out at Rayleigh numbers of 10^3, 10^4,10^5 and 10^6 , Hartmann numbers of 0, 10 and 50, horizontal angles with cavity of 0°, 30°, 60° and volume fractions of 0 to 4%. The results show that:

1) With the increase of applied magnetic field strength (Hartmann number increases) due to the effect of Lorentz force, velocity and thus the power of nanofluids in the enclosure decreases.
2) Increasing the Hartmann number, the natural convection reduces and given the Hartmann number, behavior of nanoluids gets more close to thermal conductivity than natural convection.
3) At all checked angles and Rayleigh numbers, average Nusselt number decreases with increasing the Hartmann number.
4) With increasing λ, the values of Nusselt number decrease at all ranges of Rayleigh numbers.
5) At all studied Rayleigh and Hartmann numbers, with increasing volume fraction of nanoparticles, the average Nusselt number increases.
6) With increasing Rayleigh number at all investigated angles, volume fractions and Hartmann numbers, the average Nusselt number increases.

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Nomenclature

B	Magnetic field (T)
c_P	Specific heat ($Jkg^{-1}K^{-1}$)
d_f	molecule water diameter of (nm)
d_p	nanoparticles diameter of (nm)
L	height of the enclosure (m)
Ha	Hartmann number
k	Thermal conductivity ($Wm^{-1}K^{-1}$)
p	pressure (pa)
Pr	Prandtl number
Ra	Rayleigh number
T	temprature (K)
T_H	hot wall temprature (K)
T_c	cold wall temprature (K)
	Greek symbol
α	thermal diffiusivity (m^2s^{-1})
β	thermal expansion coefficient (K^{-1})
μ	viscosity ($kgm^{-2}s^{-1}$)
υ	dynamic viscosity (m^2s^{-1})
θ	Dimensionless temperature
ρ	Density (kgm^{-3})
φ	Nanoparticles volume fraction
	Subscripts
Av	average
g	
c	cold
f	fluid
h	hot
nf	nanofluid
p	particle

چکیده

هدف از این تحقیق بررسی اثر میدان مغناطیسی بر جریان و انتقال حرارت در جابه‌جایی طبیعی نانوسیال آب – اکسید مس با خواص متغیر در محفظه‌ی مربعی کج شده می‌باشد. دیواره‌های افقی محفظه عایق بوده، دیواره‌ی جانبی سمت چپ گرم و دیواره‌ی جانبی طرف راست سرد است. مطالعه برای اعداد رایلی 10^3، 10^4، 10^5 و 10^6، اعداد هارتمن ۰، ۱۰ و ۵۰، زاویه‌های محفظه 0°، 30° و 60° با راستای افقی و کسرهای حجمی ۰، ۰/۰۲ و ۰/۰۴ از نانوذرات انجام شده است. معادلات حاکم با روش حجم محدود و الگوریتم سیمپلر به‌صورت عددی حل شدند. نتایج نشان دادند با اعمال میدان مغناطیسی و افزایش آن، سرعت نانوسیال و در نتیجه قدرت جریان کاهش یافته و رفتار نانوسیال از جابه‌جایی طبیعی به رفتار نانوسیال در هدایت حرارتی نزدیک می‌شود. در همه‌ی اعداد رایلی و کسرهای حجمی با افزایش عدد هارتمن، عدد ناسلت متوسط کاهش می‌یابد. همچنین با افزایش زاویه محفظه با افق مقادیر عدد ناسلت در همه‌ی اعداد رایلی کاهش می‌یابد.