Effect of the three main directions of an external magnetic field on the free convection in Fe_3O_4- water nanofluid filled cubic enclosure

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Abstract: The present work studies numerically the influence of the three main directions of an external magnetic field on Fe_3O_4-water nanofluid free convective flow within a cubic enclosure subjected to horizontal temperature gradient. The MHD problem is mathematically modeled, and its dimensionless equations are established. The system of partial differential equations, governing the phenomenon, is resolved by a numerical approach based on the finite volume method using ANSYS Fluent. The impact of Rayleigh number $(10^3 \leq Ra \leq 10^6)$, Hartmann number $(0 \leq Ha \leq 20)$ and the three principal magnetic field directions on thermo-hydrodynamics behavior of nanofluid is also studied. This study is carried out for pure water $(\emptyset = 0)$ and for a nanofluid with low solid volume fraction $(\emptyset = 0.02)$. The correlations chosen for calculating thermal conductivity and dynamic viscosity are specifically developed for Fe_3O_4-water nanofluid from previous experimental studies. Simulation results reveal that the decrease of Nusselt number with increasing magnetic field strength becomes stronger with increasing the Ra number. Applying magnetic field horizontally i.e. parallel to the temperature gradient, decreases heat transfer greater than in the other two directions. In second position, the most significant reduction in convective heat transfer rate is recorded when magnetic field direction is vertical i.e. parallel to gravity.

Keywords: Cubical enclosure, Magnetic field direction, Fe_3O_4-water nanofluid, Natural convection.

1. INTRODUCTION

The problem of the influence of an externally applied magnetic field (MF) on free convection in square-shaped closed cavities containing nanofluids (nnfs) has been the focus of numerous numerical and experimental investigations during the last years [1-10]. This is because of its widespread industrial uses, such as crystal growth fluids, electronic equipment cooling, melt casting, geothermal energy extraction, purification of molten metals, nuclear reactors, etc.… The nanofluid is produced from the suspension of metallic, oxide metallic or non-metallic nanoparticles (nnps) in the conventional fluid commonly used such as water and oil. The nnf was first proposed by Choi [11]. The relatively high thermal conductivity of nnps increases the nnf thermal conductivity. In some cases, the use of nnfs as the working medium, greatly enhances the free convection rate; hence, the need to control this improvement. The Lorentz forces developed by the external MF application, slow down the convective currents and thus allow the control of the high heat transfer rate. One of the biggest problems with nnfs substances is the precision of models for calculating their dynamic viscosity and thermal conductivity. While, there are many researches on modeling efficient properties, some scientists show that using certain correlations can perform to false predictions of these properties [12]. D. Toghraie et al. [13] determine experimentally the (Fe_3O_4-water) dynamic viscosity. The viscosity measurements were made between 293 K to 328 K with low volume fraction of nnps $(\emptyset \leq 3\%)$. Results show the significant decrease of the viscosity with the increase of the temperature. In addition, the viscosity augments greatly as the volume fraction of nnps increases. The dynamic viscosity model developed by these researchers [13] is chosen for this work. M. Afrand et al. [14] propose a correlation to estimate the Fe_3O_4-water thermal conductivity. For this study, this correlation is adopted.

This study aims to present a three-dimensional numerical simulation of the convective flow comportment of nnf into a cubical cavity when the base fluid, which is water, is seeded with low volume fraction of Fe_3O_4 np. A uniform magnetic field is externally applied on the cavity, each time, in one of the main directions x, y or z. Calculations were made to establish the relation between heat exchange enhancement and magnetic field direction. The models used for calculating thermal conductivity and effective dynamic viscosity are correlations experimentally determined specifically for Fe_3O_4-water nanofluid.

2. MATHEMATICAL AND NUMERICAL MODELISATIONS

2. 1. Problem geometry

Fig. 1 schematizes the cubical enclosure of side L. The Fe_3O_4-water nnf is enclosed in the cavity and subjected to horizontal temperature gradient. The lateral left wall is kept at a certain temperature T_h, and the right one is kept at a lower temperature T_c. The four remaining walls are supposed to be insulating. The direction of a uniform MF externally applied is changed in the three main directions. A Cartesian system (x, y, z) is adopted. Gravity acts along the negative z direction and the temperature difference is imposed in the x direction.

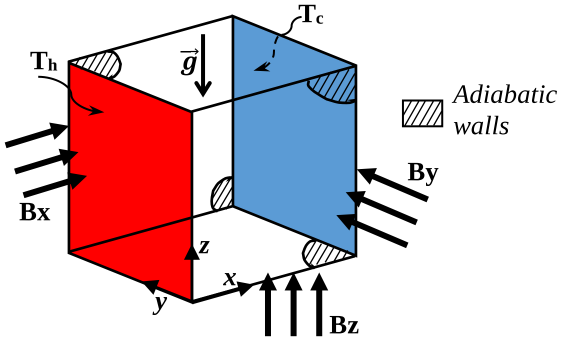


Figure 1. Problem geometry

2. 2. Mathematical model

The nnf flow into the cubical cavity, is considered laminar, steady and incompressible. The nnf is Newtonian. It is important to explain here that the Newtonian nnf hypothesis used for this simulation is absolutely valid. Since the base fluid used is the water, which is a Newtonian fluid, and the solid volume fraction considered is relatively low $(\emptyset = 0.02)$, the behaviors of the nnf and the base fluid can be considered as similar. The Fe_3O_4 solid particles and the water are supposed in thermal equilibrium, so, the single-phase model is used in this study. According to Boussinesq hypothesis, all the thermo-physical nnf properties are constant, with the exception of the term of density variation. The displacement currents, radiation heat transfer, viscous dissipation, Joule effect and induced magnetic field are neglected. The MF vector of constant magnitude is expressed by: $\vec{B} = B_0\,\overrightarrow{e_B}$. Where $\overrightarrow{e_B}$ represents the unit vector. When MF is applied horizontally parallel to the temperature gradient, the MF vector is expressed by: $\vec{B} = \overrightarrow{B_x} = B_0\,\vec{\imath}$. If the MF field direction is parallel to gravitational field, its vector is written as : $\vec{B} = \overrightarrow{B_z} = B_0\,\vec{k}$. In the case where the MF is applied perpendicularly to both directions horizontal and vertical, its vector is: $\vec{B} = \overrightarrow{B_y} = B_0\,\vec{\jmath}$. The electromagnetic force $\vec{F}$ is defined by $\vec{F} = \vec{J} \times \vec{B}$ where $\vec{J}$ the electric current is given by: $\vec{J} = \sigma\left[-\nabla\Phi + \left(\vec{V} \times \vec{B}\right)\right]$. By using $(T_h - T_c)$, L, α_f/L, and $\rho_{nf}\,\alpha_f^2/L^2$ as typical scales for temperature, lengths, velocities, and pressure, respectively, the dimensionless governing equations are:

$$\nabla.\vec{V} = 0 \tag{1}$$

$$(\vec{V}.\nabla)\vec{V} = -\nabla P + \frac{\mu_{nf}}{\alpha_{nf}\rho_{nf}}\,\nabla^2\vec{V} - \frac{\rho_f\,\beta_{nf}}{\rho_{nf}\beta_f}\,Ra\,Pr\,T\vec{k} + \frac{\sigma_{nf}\,\rho_f}{\sigma_f\,\rho_{nf}}Ha^2\,Pr\left[\left(\vec{V} \times \overrightarrow{e_B}\right) \times \overrightarrow{e_B}\right] \tag{2}$$

$$\vec{V}.\nabla\theta = \left(\alpha_{nf}/\alpha_f\right)\nabla^2\theta \tag{3}$$

Where dimensionless numbers are given by: Rayleigh number: $Ra = \frac{g\,\beta_f\,(T_h - T_c)\,L^3}{\nu_f\ \alpha_f}$; Hartmann number: $Ha = B_0\,L\sqrt{\frac{\sigma_{nf}}{\rho_{nf}\mu_f}}$ and Prandtl number: $Pr = \frac{\nu_f}{\alpha_f}$. The other parameters appearing in Eqs. [1]-[3] are explained in the following paragraph. . No slip condition is supposed on all walls. $T = T_h$ for the left wall, $T = T_c$ for the right wall and ${}^{\partial T}/{}_{\partial n} = 0$ for the other four walls are the thermal boundary conditions adopted for this problem.

2. 3. Nanofluid thermo-physical properties

The Fe_3O_4-water effective density, specific heat, and thermal expansion coefficient [15, 10], are expressed by:

$$\rho_{nf} = (1 - \emptyset)\,\rho_f + \emptyset\,\rho_s \tag{4}$$

$$\left(\rho\,c_p\right)_{nf} = (1 - \emptyset)\left(\rho\,c_p\right)_f + \emptyset\left(\rho\,c_p\right)_s \tag{5}$$

$$(\rho\,\beta)_{nf} = (1 - \emptyset)\,(\rho\,\beta)_f + \emptyset\,(\rho\,\beta)_s \tag{6}$$

In the above equations, *f*, *nf* and *s* are indices indicating base fluid, nnf and nnps respectively.

The Maxwell model [16] is used to calculate nanofluid electrical conductivity:

$$\sigma_{nf} = \sigma_f\left[1 + \frac{3\,\emptyset\,(c-1)}{(c+2) - \emptyset(c-1)}\right] \tag{7}$$

Where $c = \sigma_s/\sigma_f$.

For small solid volume fractions of Fe_3O_4-water, correlations have been developed experimentally for computing the dynamic viscosity [13] and thermal conductivity [14]. These correlations are chosen to model these physical properties respectively:

$$\mu_{nf} = \mu_f(1.01 + 0.007165\,T^{1.171}\emptyset^{1.509})\,\exp(-0.00719\,T) \tag{8}$$

$$k_{nf=}k_f(0.7575 + 0.3\,\emptyset^{0.323}T^{0.245}) \tag{9}$$

Where T is in °C and ϕ is in %.

At the left hot wall, the local Nu number is calculated by:

$$Nu = -\left(k_{nf}/k_f\right)(\partial\theta/\partial X)_{X=0} \qquad (10)$$

and the average Nu number is defined by:

$$Nu_{avg} = \int_0^1 \int_0^1 Nu\, dY\, dZ \qquad (11)$$

2. 4. Numerical method

The simulations are made through ANSYS fluent 14.5, based on finite volume method developed by Patankar [17]. For coupling pressure and the velocity field, the SIMPLE algorithm is adopted, and for pressure discretization a PRESTO scheme is applied. The 2-order upwind-scheme is chosen for discretizing the convection-diffusion terms.

2. 5. Grid independency

A test of sensibility of five mesh sizes is conducted as shown in Table 2. The Nu_{avg} is calculated for natural convection of Fe_3O_4-water nnf when $Ra=10^4$, $\phi = 0.01$, $Ha = 10$ with MF applied in temperature gradient direction (Bx). The code convergence test for this simulation is : $max|\Gamma^{n+1} - \Gamma^n| < 10^{-6}$ where Γ replaces the unknown variables (U, V, W, θ) describing the thermos-hydrodynamic behavior in the cavity and n is the number of iterations. A grid size of 71^3 is chosen because it ensures the grid independent solution and gives a good agreement between the precision and the calculation time.

Table 2. Grid independency, $Ra = 10^4$, $\phi = 0.01$, $Ha = 10$ (Bx)

Mesh size	41^3	51^3	61^3	71^3	81^3
Nu_{avg}	1.9998	1.9452	1.9261	1.9266	1.9267

2. 6. Validation of the solution

The code used in this simulation is validated by the results found by Al-Rashed study [2]. Fig. 2 shows a good agreement with the Nu_{avg} values at hot wall for CuO-water nnf filled a cubical cavity for $Ra = 10^5$ with horizontal external uniform MF (Bx) and for three Ha values (0, 50 and 100).

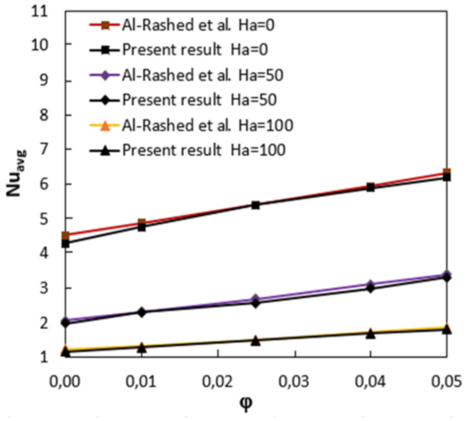
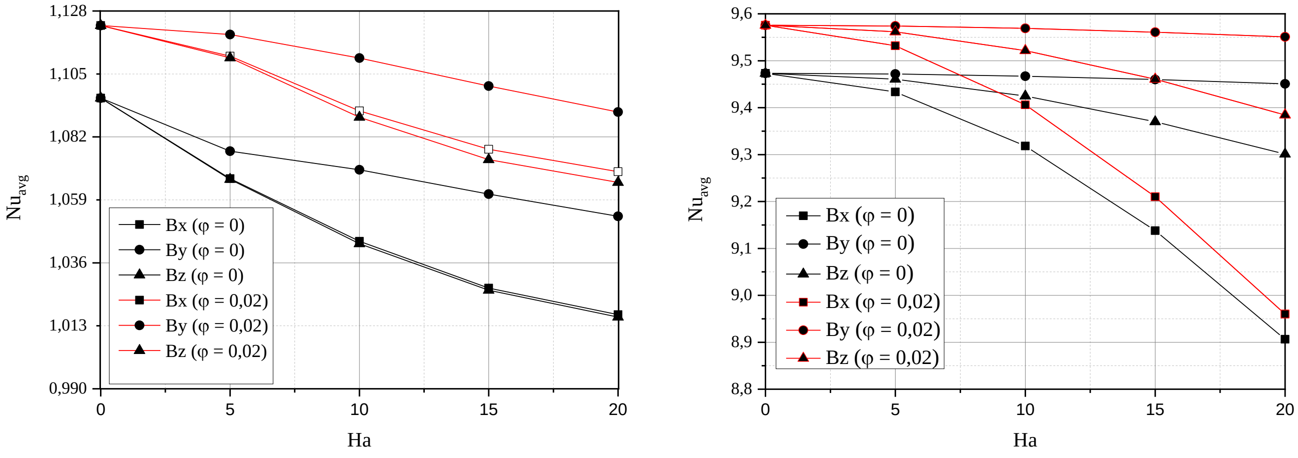


Figure 2. Present code validation with results of Al-Rashed et al. [2]

3. RESULTS AND DISCUSSION

This study was realized, first, for pure water ($\emptyset = 0$) and then for Fe_3O_4-water nnf ($\emptyset = 0.02$). The simulations are carried out for five values of MF strength, four Rayleigh numbers (Ra), and for three main directions of MF. Fig.3(a) and Fig.3(b) present the variation of the dimensionless number (Nu_{avg}), reflecting the rate of convective heat transfer at the left hot wall, depending on Ha number (in each direction separately) for pure water ($\emptyset = 0$) and for nnf ($\emptyset = 0.02$) and this, for $Ra = 10^3$ and $Ra = 10^6$ respectively. The first thing to notice, that a raise in $\emptyset$ conducts to higher heat transfer rate in all MF directions. Also, the diminution in the Nu_{avg} with the augmentation of Ha, resulting from the development of Lorentz magnetic forces is clearly visible for the three MF directions. It is also interesting to conclude from these two figures, the clear and net effect of varying MF direction on the amount of the convective heat transfer within this studied cavity. The most significant reduction in the heat transfer is recorded when the direction of MF is horizontal, i.e. parallel to the temperature gradient. In second position, for the decrease of heat transfer rate, comes the vertical direction z of the MF, i. e. parallel to the gravitational field. Fig. 4 illustrates the Ra influence on (Nu_{avg}) for (Ha=20), for $\emptyset = 2\%$ and for the MF applied in each of the three directions. The buoyancy forces that increase by raising Ra greatly enhance the rate of thermal transfer for the three MF directions. In this figure, it is noteworthy that the largest decrease in Nu_{avg} is recorded when MF is directed along the x-axis which is consistent with the above results. Fig. 5 presents the effect of increasing Ha on (Nu_{avg}) for four values of Ra, for ($\emptyset = 0.02$) and when the application of MF is directed horizontally along x axis (Bx). The attenuation effect on heat transfer caused by raising Ha visibly increases with the increase in Ra. This means that the Lorentz forces developed by MF presence, work better at reducing heat transfer when the natural convection regime is dominant.



(a) *(b)*

Figure 3. Nu_{avg} at the hot wall with Ha for three MF directions. (a) Ra=10^3, (b) Ra=10^6

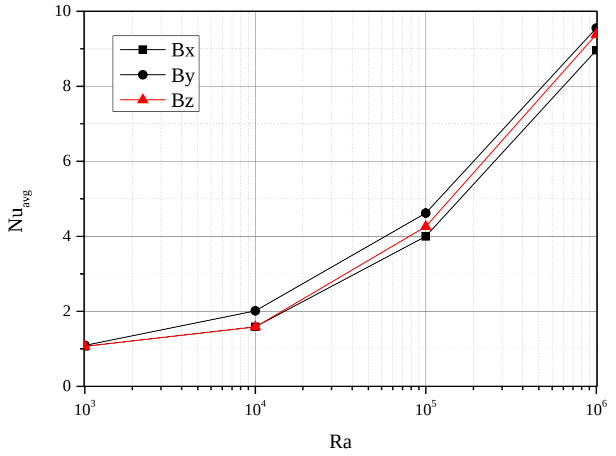


Figure 4. Nu_{avg} at hot wall with the Ra for Ha=20, for three directions of MF and for $\emptyset = 0.02$

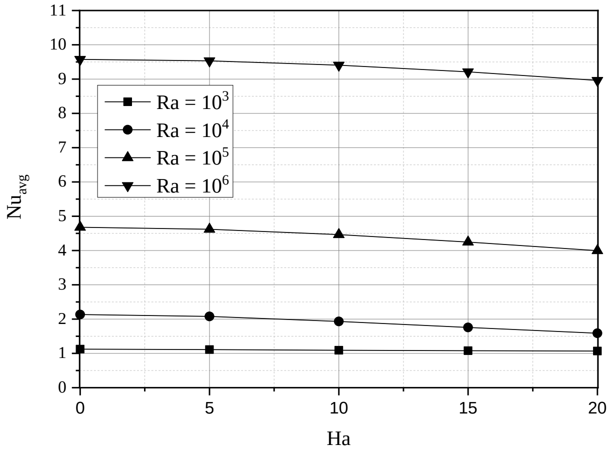


Figure 5. Nu_{avg} at hot wall with Ha, Bx and $\emptyset = 0.02$

4. CONCLUSION

Numerical 3D simulations were carried out in order to shed light on the effect of changing the direction of a MF applied externally to a cubical enclosure on the natural convection of the Fe_3O_4-water nanofluid which fills it. The direction of MF changes along the three main axis. Results indicate that MF can be used for controlling natural convection in a cubical enclosure. Free convection in the cavity is enhanced with augmentation of buoyancy forces and solid volume fraction but suppressed with rise of Lorentz force resulting from the application of a uniform external MF in one of the three main directions. As the magnetic field magnitude augments, the decrease slope of the Nu number increases with growing Ra number. Applying the magnetic field in the horizontal direction (parallel to temperature gradient) dampens the convection to a greater degree than in the other two directions. In second place, in terms of damping, comes vertical direction of magnetic field (gravity direction).

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