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Effects of inclination and magnetic field on natural convection of nanofluids in a partially heated cubic enclosure

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***Abstract*—In this paper three-dimensional of natural convection heat transfer of Al_2O_3 water nanofluid in a differentially-heated, cubic enclosure has been studied numerically. The effects of nanoparticles volume fraction, Rayleigh number, Hartman number and inclination angle on natural convection heat transfer are analyzed. . Method of solution is based on the finite volume method and an accelerated multigrid which has been tested and compared with previously published work on the basis of special cases and proved excellent agreements. The average Nusselt number increases with the increase of nanoparticles volume fraction at Ra=10^5 for Al_2O_3 water nanofluid. It is observed that the applying magnetic field results in a force opposite to the flow direction that leads to drag the flow and then reduces the convection currents by reducing the velocities. It has been noticed that the flow is affected by the number of Hartman and the inclination of the angle.**

***Keywords*—natural convection, Heat transfer, Magnetoconvection, Nanofluids, three-dimensional, inclination angle.**

I. INTRODUCTION

Natural convection in differentially heated inclined cavities was the subject of an important number of researches. To study the effect of this inclination on heat transfer and fluid flow, authors choose different ranges of angles.

Ravnik et al. [1] studied on the flow and heat transfer characteristics of the natural convection nanofluid flows in closed cavities. The simulations performed for Rayleigh number and three types of water-based nanofluids by using a three dimensional boundary element method based on flow solver. They have shown that the use of water-based nanofluids instead of pure water improves heat transfer.

Sheikholeslami and Ellahi [2] used the Boltzmann grid to study nanofluid natural convection inside a 3D enclosure in the presence of magnetic field. The Brownian motion was taken into account in the model used for the nanofluid coefficient of conductivity and viscosity. According to their results, magnetic field had a significant impact on natural convection heat transfer. In addition, the fluid convection decreased by increasing the Hartmann number. They also reported that, at a Rayleigh number of 10^5, the heat transfer rate is highly dependent on the Hartmann number. However, this dependency is decreased at smaller Rayleigh numbers.

Zhou et al. [3] performed a three-dimensional lattice Boltzmann simulation for mixed convection for nanofluid filled enclosure in presence of magnetic force. The influences of Rayleigh number, solid volume fraction of nanofluid, Hartmann number and Richardson number on the fluid flow and heat transfer are studied. They showed that the Adding nanoparticles of Al_2O_3 into pure water improve natural convection heat transfer in a cubic cavity. However, the effect of convective heat transfer enhancement is more pronounced at low Rayleigh numbers. The enhancement will be weakened and even reversed at high Rayleigh numbers. (2) In contrast to Rayleigh number, the increase of Hartmann number decreases the heat transfer rate. This effect is more pronounced at high Rayleigh numbers. In addition, the influences of external magnetic field on heat transfer vary with different orientations.

Kolsi et al. [4] performed a computational study for 3D MHD natural convection inside a cubical enclosure with an inclined plate. They found an optimal inclination angle for the plate. The maximum heat transfer is formed when h = 180° but minimal value of average Nusselt number is changed according to nanoparticle addition into base fluid. Also, a minimum heat transfer value is formed at h = 270° almost for all cases. But effects of inclined plate became clearer for higher values of Rayleigh number. Heat transfer increases with increasing of Rayleigh numbers

Krunul and Gangawane [5] made a study on natural convection in a partially heated open ended square cavity subjugated to a magnetic field by using thermal lattice Boltzmann method (TLBM) based on single relaxation time (SRT) method. He showed that cavity with the applied magnetic field at Ha=45 offers highest heat transfer restriction than other considered cases.

Mahian et al. [6] performed a theoretical and experimental study on the Natural convection of silica nanofluids in square and triangular enclosures. Results indicate that the average Nusselt number could be estimated theoretically with the same trend and maximum difference of 4.5%.

Kolsi et al. [7] investigated the combined buoyancy-thermocapillary convection in 3D enclosure filled with Al2O3

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nanofluid and showed that the increase of nanoparticle volume fraction causes heat transfer enhancement.

II. PHYSICAL MODEL AND NUMERICAL APPROACH

A. Physical Model

As shown in Figure 1, a three-dimensional cubic enclosure of side length *L* filled with Al_2O_3-water nanofluid is considered (*Pr*=6.2). The right sidewall of the enclosure is maintained at a constant hot temperature *T*H, while the opposite wall has a constant cold temperature *T*C. Four other walls of the enclosure are adiabatic. The nanofluid is assumed to be Newtonian, incompressible and the flow is laminar. The thermophysical properties of the base fluid (water) and Al2O3 nanoparticles are given in Table 1. The thermophysical properties of the nanofluid are taken to be constant except for the density variation in the buoyancy force, which is estimated by using the Boussinesq approximation. An external magnetic field is located at the center of the left hot wall which induced the magnetic convection at an angle of γ.

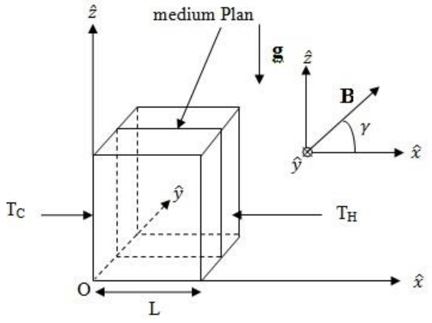

Fig. 1. Physical model

Table.1: Thermophysical properties of water and Al_2O_3 nanoparticles.

	Pure water	**Al_2O_3**
$\rho(Kg\ m^{-3})$	997.1	3,970
$C_p(JKg^{-1}K^{-1})$	4179	765
$\nu(m^2.s^{-1})$	0.613	40
$\beta(K^{-1})$	21×10^{-5}	85×10^{3}
$K(W\ m^{-1}\ K^{-1})$	1.74×10^{7}	131.7×10^{7}
$\sigma(\Omega^{-1}\ m^{-1})$	0.05	10^{-12}

.

B. Numerical approach

Based on the above assumptions, the governing dimensionless equations for conservation of mass, momentum, and energy of the three-dimensional unsteady nanofluids magnetoconvection (MHD) flow can be written as follows*:*

Conservation of mass equation:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}+\frac{\partial V}{\partial Y}=0 \qquad (1)$$

Momentum equation:

Projection according to (ox):

$$\frac{\partial U}{\partial \tau}+U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}+W\frac{\partial U}{\partial Z}=-\frac{\partial P}{\partial X}+\frac{\nu_{nf}}{\nu_f}\Pr\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}+\frac{\partial^2 U}{\partial Z^2}\right)+$$

$$\frac{\sigma_{nf}}{\sigma_f}\Pr Ha^2\sin(\gamma)\left(-U\sin(\gamma)+W\cos(\gamma)\right) \qquad (2)$$

Projection according to (oy):

$$\frac{\partial V}{\partial \tau}+U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}+W\frac{\partial V}{\partial Z}=-\frac{\partial P}{\partial Y}+\frac{\nu_{nf}}{\nu_f}\Pr\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}+\frac{\partial^2 V}{\partial Z^2}\right)+$$

$$\frac{\sigma_{nf}}{\sigma_f}\mathrm{Pr\ Ha^2\ V} \qquad (3)$$

Projection according to (oz):

$$\frac{\partial U}{\partial \tau}+U\frac{\partial W}{\partial X}+V\frac{\partial W}{\partial Y}+W\frac{\partial W}{\partial Z}=-\frac{\partial P}{\partial Z}+\frac{\nu_{nf}}{\nu_f}\Pr\left(\frac{\partial^2 W}{\partial X^2}+\frac{\partial^2 W}{\partial Y^2}+\frac{\partial^2 W}{\partial Z^2}\right)$$

$$-\frac{\beta_{nf}}{\beta_f}Ra\Pr\theta+\frac{\sigma_{nf}}{\sigma_f}\Pr Ha^2\cos(\gamma)\left(U\sin(\gamma)-W\cos(\gamma)\right) \qquad (4)$$

Energy equation:

$$\frac{\partial \theta}{\partial \tau}+U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}+W\frac{\partial \theta}{\partial Z}=\frac{\alpha_{nf}}{\alpha_f}\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}+\frac{\partial^2 \theta}{\partial Z^2}\right) \qquad (5)$$

In order to cast the governing equations into a dimensionless form, the following dimensionless parameters are introduced:

$$Ra=\frac{g(T_H-T_C)\mathrm{H}^3\beta_f}{\upsilon\alpha}\ ;\ \Pr=\frac{\upsilon_f}{\alpha_f}\ ;\quad Ha=LB\sqrt{\frac{\sigma_f}{\mu_f}}$$

The average Nusselt number (Nu_{avg}) is defined in the heated wall as:

$$Nu_{avg}=-\frac{K_{nf}}{K_f}\int_0^1\left.\frac{\partial\theta}{\partial Y}\right|_{Y=0}dX$$

III. RESULT AND DISCUSSION

The presented results in this work are obtained by using a finite volume home FORTRAN code, named NASIM and developed by the second author which use multi-grid solver explained in details in previous works [8].

In this section, we will adopt the multi-grid solver to study the natural convection of nanofluids in partially heated cubic enclosures
with temperature-dependent properties. Numerical simulations are performed for wide ranges of different parameters:

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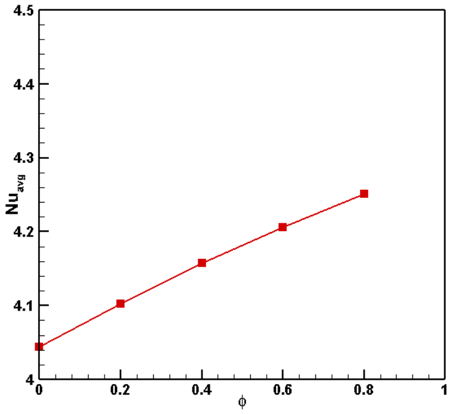
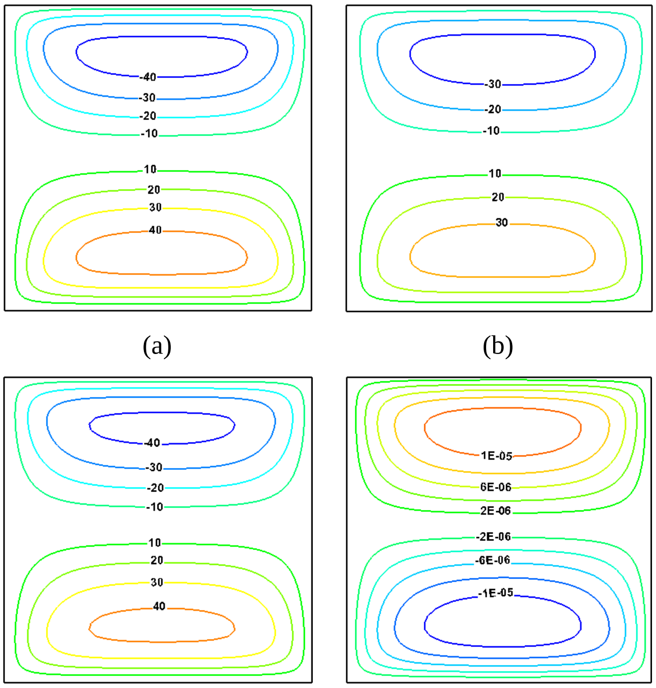


Fig.2. Comparison of the average Nusselt for various volume fraction at Ra=10^5



(a) (b)

(c) (d)

Fig.3. Comparison of the stream line velocity for various inclined angles (a) 0°, (b) 30°, (c) 60°, (d) 90° at Ra=10^5.

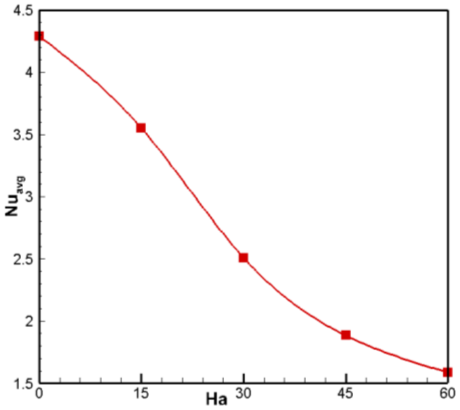
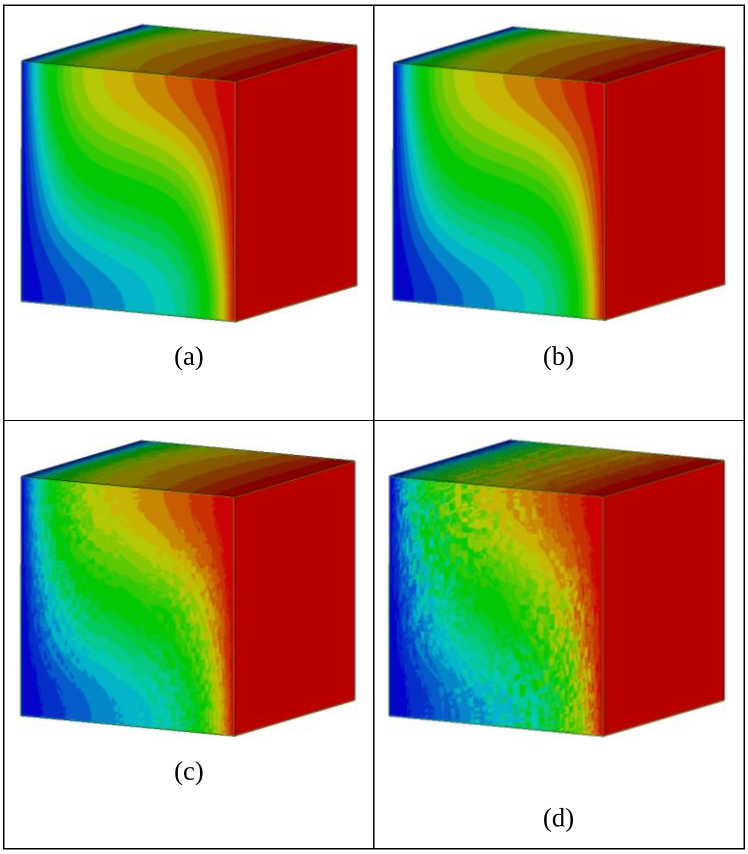


Fig.4. Comparison of the average Nusselt for various Hartman number at Ra=10^5 and γ=45°



(a) (b)

(c) (d)

Fig.5. Effects of inclination angle (a) Ha= 0, (b) Ha=15, (c) ha= 30, (d) Ha= 60 on isotherms (Ra = 1 × 105, ϕ=1%, (γ) =45°).

In order to study the effects of the external applied magnetic field on heat transfer, a series of simulation tests were performed within a partially heated cubic cavity.

Figure 2 Figure shows the effects of volume fractions of nanoparticles on the natural convection heat transfer of nanofluids in a cubic cavity. Four simulation cases, namely, φ = 0, 2%, 4%, 8%, at Ra=10^5 have been realized. It is observed that the addition of nanoparticles in the base fluid improves the heat exchange rates in the fluid and consequently leads to the improvement of the energy transfer.

For pure water and Al_2O_3-water nanofluids, figure 3 present the the stream line velocity for various inclined angles at Y=0 and Ra=10^5. it has been shown that the speed of the flow is affected by the angle of inclination.

Figure 4 illustrates the variation of average Nusselt number with Hartmann
number at Rayleigh numbers 10^5. As can be seen in the figure, the increase of
the Hartmann number decreases the heat transfer rate.It is interesting to see that this fact is not valid for Ha=60 and

Ha=30. For lower Ha numbers, the magnetic forces are weaker so the flow is not totally under the influences of these forces. Figure 5 presents the effects of Hartmann number on isotherms. It is observed the isotherms become parallel to the side wall as Hartmann number increases. It is due to the increase of Hartmann number leads to increasing Lorentz force, which results in the domination of conduction heat transfer.

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