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Received 09 January 2011; accepted 04 March 2011

Journal of Scientific Research
ISSN 2170-1237

Journal of Scientific Research

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Journal of Science Research N 1, Vol. 1, p. 29-33

Heat transfer in an inclined ferrofluid with a transverse magnetic field

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Abstract – *In the present study, the natural convection of magnetic fluid in an inclined square cavity is studied numerically, the physical model is heated from left –hand side vertical wall and cooled from opposing wall. A finite-volume method is used to discredit the Navier-stokes and energy equations. The SIMPLER algorithm was used to solve the coupled heat transfer and flow problem. The inclination angle varies from 0° to 90°. The results show that the inclination angle has significant effect on the flow and heat transfer.*

Keywords: *Magnetic Fluid. Natural Convection. Magnetic Gradient Field. Inclination*

I. INTRODUCTION

Ferrofluids (known also as magnetic fluids) are a special category of smart nanomaterials, in particular magnetically controllable nanofluids. These types of nanofluids are colloids of magnetic nanoparticles, such as Fe_3O_4, γ-Fe_2O_3 or $CoFe_2O_4$, stably dispersed in a carrier liquid such as kerosene, heptane or water. Consequently, these nanomaterials manifest simultaneously fluid and magnetic properties. This fluid combines three main properties: (i) it is an efficient contrast agent for magnetic resonance imaging (MRI); (ii) its magnetic behaviour allows possible magnetic guiding towards biological site under magnetic field gradient; (iii) it can be used for treatment by hyperthermia by applying alternative magnetic field. The possibility of controlling the position and properties of a fluid using a magnetic field has opened up diverse fields of applications research. So, an extensive work has been done in this field [1-6].In certain applications, such as in energy conversion devices, it is necessary to use a fluid with large pyromagnetic coefficient K, i.e., with a high saturation magnetization and a low Curie temperature.

Heat transfer characteristics associated with natural convections of the magnetic fluids have been a subject of interest to engineers and scientists for many years [9–13]. Yamaguchi et al [9,10] studied experimentally and numerically the natural convection of a magnetic fluid in a two dimensional cell, whose aspect ratio is one. The Results obtained from experiment and numerical analysis revealed that the vertically imposed magnetic field has destabilizing influence and at the super critical state the flow mode becomes different from that without the magnetic field. The natural convections of the magnetic fluid in a square Hele-Shaw cell were experimentally investigated with heat transfer measurements and liquid crystal thermography by Wen and Shu [11,12]. The results confirmed the findings of Yamaguchi et al. [9,10]. In numerically studying, the works of Yamaguchi et al. [9,10], Krakov and Nikiforov [13] discovered that the angle between the directions of temperature gradient and the magnetic field influences the convection structure and the intensity of heat flux. Three-dimensional natural convections of a magnetic fluid in a cubic cavity under a uniform magnetic field are investigated experimentally and numerically by yamaguchi et al [14]. The Results obtained from experiments and numerical simulations reveal that the magnetic field and magnetization are influenced by temperature.

The study of thermomagnetic convection in inclined enclosures is motivated by desire to find out any effects of the slope on thermally driven flows which are found in many engineering applications. In this field Wang and al [15] studied numerically the natural convection of paramagnetic fluid (air) in an inclined enclosure under magnetic field. The results show that both the magnetic force and the inclination angle have significant effect on the flow field and heat transfer in porous medium. In the present work, two-dimensional laminar natural convection flows of the magnetic fluid in an inclined square cavity under horizontal uniform magnetic gradient field are studied numerically. Particularly the effects of inclination angle on the heat transfer characteristics and flow and temperature behaviours are investigated.

II-PHYSICAL MODEL

The physical model considered in this paper are shown schematically in Figure1.The ferrofluid confined in an inclined square cavity is heated uniformly from vertical wall and cooled from an opposing vertical wall. The other walls are thermally insulated. Angle of inclination measured from horizontal plate to the adiabatic wall of the enclosure. The cavity is subjected to the horizontal uniform magnetic gradient field. The inclination angle (φ) varies from 0° to 90°.

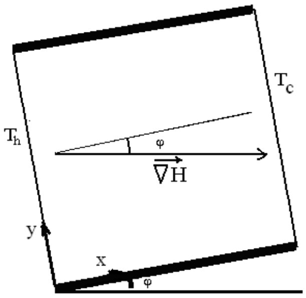


Figure 1. Physical models

In this work the magnetic fluid is similar to that used in [16] (a water-based magnetic fluid, with density ρ=1180 kg/m^3, kinematical viscosity ν= 1.69×10^{-6} m^2/sec, coefficient of thermal diffusivity α =0.119 10^{-6} m^2/sec and saturation magnetization Ms=15.61×10^3 A/m). The Prandtl number of this fluid is Pr= 14.20

III-MATHEMATICAL MODEL

The mathematical model consists of equations of masse balance, energy balance and momentum balance. Ferrohydrodynamics model used is that of Neuringer-Rosenweig [17]. In this model the following assumptions are adopted: The ferrofluid is an incompressible Newtonian fluid, magnetization saturated. Neglecting displacement currents, induced magnetic fields, dissipation viscous, magnetocaloric effect in the energy balance and using the Boussinesq approximation.

Under the above assumptions the following equations used to describe physical problem are defined by:

Continuity équation :

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

Momentum equation :

$$\vec{v}.\vec{\nabla}\vec{v}=-\frac{1}{\rho_0}\vec{\nabla}p+\nu_f\Delta\vec{V}-\beta_\rho\left(\mathrm{T}-\mathrm{T}_0\right)\vec{g}-\frac{\mu_0}{\rho_0}\mathrm{K}\left(\mathrm{T}-\mathrm{T}_0\right)\vec{\nabla}\mathrm{H} \qquad \textit{(2)}$$

Energy équation :

$$u\frac{\partial \mathrm{T}}{\partial x}+v\frac{\partial \mathrm{T}}{\partial y}=\alpha\left(\frac{\partial^2\mathrm{T}}{\partial x^2}+\frac{\partial^2\mathrm{T}}{\partial y^2}\right) \qquad (3)$$

The velocity and pressure are scaled using reference quantities α/L , $\rho\left(\alpha/L\right)^2$ respectively. Dimensionless temperature is $\theta=\left(T-T_c\right)/\left(T_h-T_c\right)$

The non-dimensional governing equations are presented in form:

$$\begin{cases} u\dfrac{\partial u}{\partial x}+v\dfrac{\partial u}{\partial y}=-\dfrac{\partial p}{\partial x}+\left(\dfrac{\partial^2 u}{\partial x^2}+\dfrac{\partial^2 u}{\partial y^2}\right)+ \\ \qquad (Rag.\sin\varphi-Ram.\cos\varphi).\mathrm{Pr}.\theta & (4) \\ u\dfrac{\partial v}{\partial x}+v\dfrac{\partial v}{\partial y}=-\dfrac{\partial p}{\partial y}+\left(\dfrac{\partial^2 v}{\partial x^2}+\dfrac{\partial^2 v}{\partial y^2}\right)+ \\ \qquad \left(Rag.\sin\varphi+Ram.\cos\varphi\right).\mathrm{Pr}\cdot\theta & (5) \\ u\dfrac{\partial \theta}{\partial x}+v\dfrac{\partial \theta}{\partial y}=\left(\dfrac{\partial^2\theta}{\partial x^2}+\dfrac{\partial^2\theta}{\partial y^2}\right) & (6) \end{cases}$$

Where Rag , Ram and Pr are the Rayleigh gravitational, Rayleigh magnetic and Prandtl numbers.

The boundary conditions for two velocity components are set to zero at all solid walls.

The temperature boundary conditions are as follows:

$$T\left(0,y\right)=1 \qquad (7)$$

$$T\left(1,y\right)=0 \qquad (8)$$

$$\left.\frac{\partial T}{\partial y}\right)_{y=0}=\left.\frac{\partial T}{\partial y}\right)_{y=1}=0 \qquad (9)$$

The heat transfer is characterized by the averaged Nusselt number defined as follow:

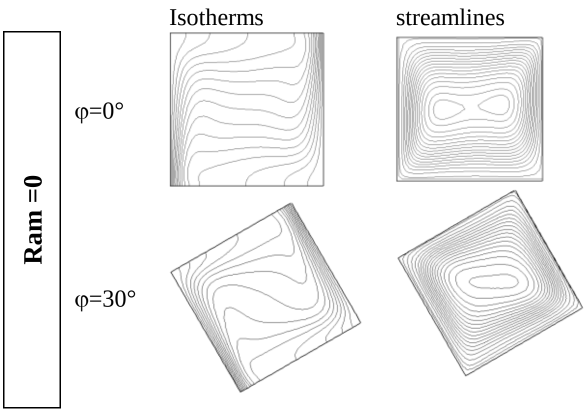
$$Nu=-\int_0^1\left(\partial\theta/\partial x\right)_{x=0}dy \qquad (10)$$

IV-RESULTS

A finite-volume method [18] is used to discretize the Navier-stokes and energy equations. The SIMPLER algorithm was used to solve the coupled heat transfer and flow problem. The discretized algebraic equations are solved by tri-diagonal matrix algorithm (TDMA). To ensure convergence of the calculus code the maximum residual of all variable in one control volume should be $<10^{-6}$ .The grid used in the present study is a uniform grid. In order to illustrate its influence on the solution of the digital code, we carried out tests for different grid varying from 21*21 to 101*101. The grid selected in the present study is 81*81. Our computer code was validated in classical case convection. We compared to the works [19,20]. The results presented in table .1. Shows an agreement between our results and those [19,20].

V.1. Effect of inclination angle on the flow and temperature fields

In order to examine effects of the inclination angle, computations are carried out for a fluid with the inclined angle (φ) varying from 0° to 90°, while other geometric parameters remained unchanged. Numerical results are obtained for $Rag=10^5$ and $Ram=10^6$.
FIGURE.2 shows the effect of inclination angle on the thermal and dynamic structure of motion in the presence and absence of magnetic gradient field at $Rag=10^5$. In the absence of magnetic gradient field and when φ=0, the hot ferrofluid rises up along the left-hand side hot wall and descends along the right-hand side cold. The distortions of isothermal and flow field increases with the angle of inclination. When φ=90° the flow are double vortices and we find the classical case of Rayleigh Benard convection heated from below. When there is magnetic field, the model equation includes the effect of magnetic force. When φ=0 and $Ram=10^6$, the rapport between the two Rayleigh numbers magnetic and gravitational equals 10 . The magnetic buoyancy, acting in the horizontal direction, opposes convection and tends to decrease heat transfer .When the magnetic gradient is important; the heat transfer flow becomes conductive. When the cavity is inclined, the two forces magnetic and gravitational have two components, horizontal and vertical. Both horizontal components are opposed and the two vertical components are in the same direction. For φ = 90°, Figure 2. shows that stratifying flow due to magnetic horizontal gradient applied.



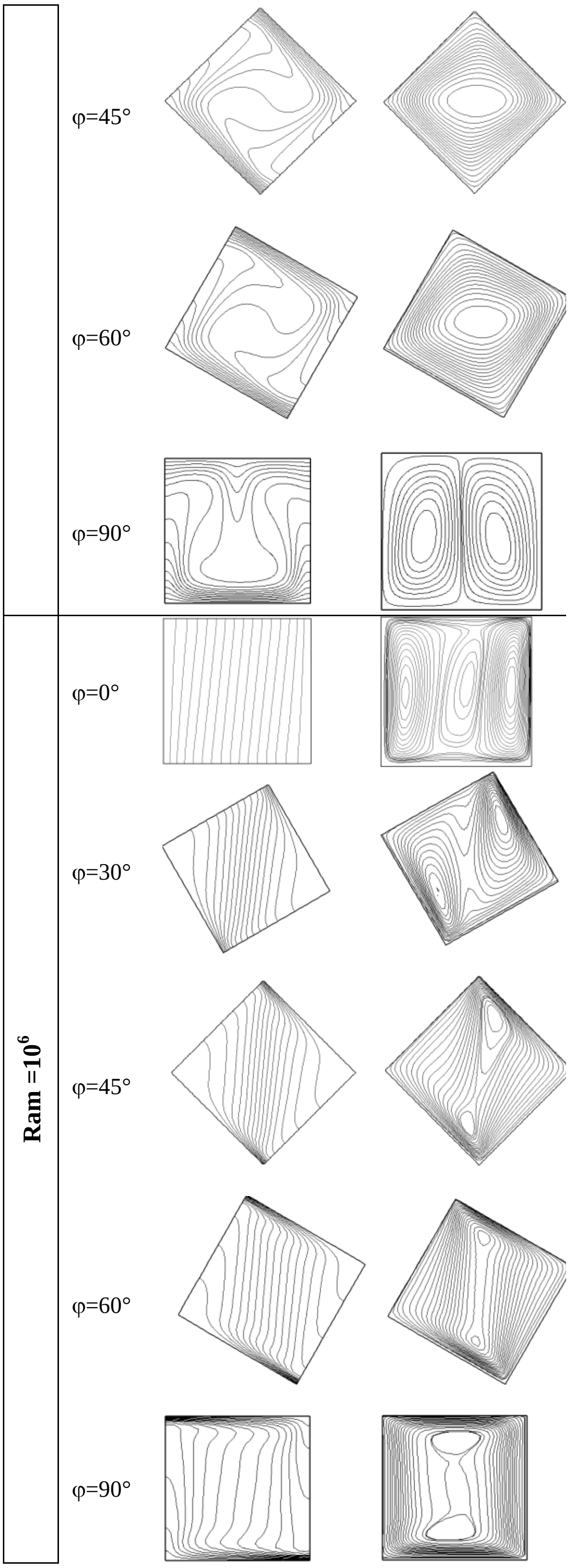


Figure 2. Isotherms and streamlines for different inclination angle

IV.2. Effect of inclination angle on the rate heat transfer

FIGURE.3 shows the effects of inclination angle on the average Nusselt number. In the absence of magnetic field where Ram=0, the heat transfer is enhanced in the interval [0°;25°] and decreases for other interval]25;90°].

When there exists magnetic field (Ram=10^6), the heat transfer is enhanced with the increase of the inclination angle. This is because the horizontal component (on the x-axis) of the gravitational force increases but the horizontal component of the magnetic force decreases, so the two other vertical components are cooperating, which promotes the flow and heat transfer. For φ=0° , compared to the previous case (no magnetic gradient) we note that the Nusselt number takes the value of the unit, which shows in this situation that the suppression of convective flow becomes possible by an adequate choice of the value and the direction of applied magnetic gradient This result was shown experimentally by Kikura et al [21] . These results show that the presence of a magnetic field gradient modify the effect of inclination for the convective heat transfer. This result was reported by Wang et al [15] in porous medium.

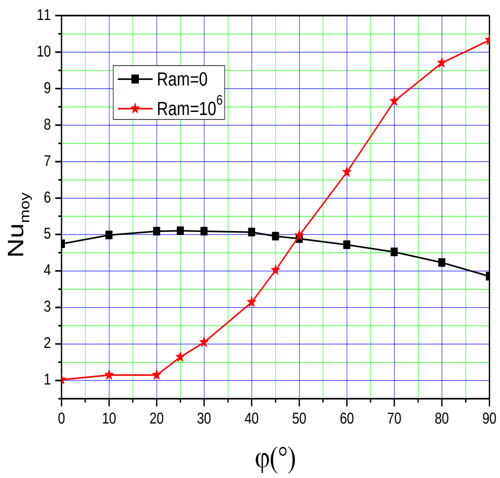


Figure3. Average Nusselt number for different inclinations angles

V. CONCLUSION

In the present work we study the effect of inclination angle of cavity for the natural ferroconvection in magnetic fluid. For a given inclination, the control of convective heat transfer becomes possible by means of an external magnetic gradient. The heat transfer is enhanced with the increase of inclination angle in the presence of magnetic gradient field and decreases in the absence of magnetic gradient field .The inclination angle has significant effect on the flow field and heat transfer.

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