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ORIGINAL ARTICLE

NUMERICAL INVESTIGATION OF NANOFLUID ISOTHERMAL LINES INSIDE A LID-DRIVEN ENCLOSURE WITH VARIOUS INCLINATION ANGLES

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ABSTRACT: In the present paper mixed convection fluid flow and isothermal lines of Al2O3-water nanofluid inside a square cavity with various inclination angles and lid's velocity ratio has been investigated numerically. The left and right side walls of the cavity were kept at Th and Tc, respectively, with Th>Tc. The top walls of the cavity moved from left to right in its own plane with a constant velocity Ut, while the bottom wall moved in its own plane from right to left with a constant velocity Ub. The velocity ratio was defined as Ub/Ut. The governing equations were discretized using finite volume method and the coupling between the velocity and pressure fields was done by SIMPLER algorithm.
KEYWORDS: Nanofluid, Variable Properties, Mixed Convection, Cavity, Finite Volume Method.

INTRODUCTION

The fundamental problem of mixed convection heat transfer in lid-driven cavity has received considerable attention from researchers. This problem is commonly encountered in a variety of engineering applications. Such applications include cooling of electronic devices, lubrication technologies, drying technologies, food processing, float glass production, flow and heat transfer in solar ponds, thermal hydraulics of nuclear reactors and dynamics of lakes. The influence of the magnetic field on the convective heat transfer and the mixed convection flow of the fluid are of paramount importance in engineering. A combined free and forced convection flow of an electrically conducting fluid in a cavity in the presence of magnetic field is of special technical significance because of its frequent occurrence in many industrial applications such as geothermal reservoirs, cooling of nuclear reactors, thermal insulations and petroleum reservoirs. These types of problems also arise in electronic packages, microelectronic devices during their operations. Mixed convection in a lid-driven cavity has received much attention. In their investigation, Iwatsu *et al.*, (1992) investigated computationally the flow of a viscous thermally stratified fluid in a square cavity. In another study, Ho *et al.*, (2008) investigated influences of uncertainties due to adapting different models for the effective thermal conductivity and the dynamic viscosity of aluminaewater nanofluid on the natural convection heat transfer in a square cavity. Their results showed that the heat transfer across the cavity could be either enhanced or mitigated with respect to that of the base fluid depending on the model used for the thermal conductivity and the viscosity of the nanofluid. Using the control volume method, Muthtamilselvan *et al.*, (2010) investigated the mixed convection heat transfer in a lid-driven rectangular enclosure filled with the Copperewater nanofluid. The enclosure's side walls were insulated while its horizontal walls were kept at constant temperatures, with the top wall moving at a constant velocity. They observed that both the aspect ratio of the cavity as well as the nanoparticles volume fraction affected the fluid flow and heat transfer inside the enclosure.

Mixed convection in enclosures for various different boundary conditions has been studied by Gebhart *et al.*, (1988) and Hasanoui *et al.*, (1990). Oztop and Varol, (2009) performed a numerical study to obtain combined convection field in inclined porous lid-driven enclosures heated from one wall with a non-uniformly heater. It was observed that flow field, temperature distribution and heat transfer are affected by inclination angle of the enclosure. Lee and Chen, (1996) obtained finite element solutions of mixed convection in a bottom heated square cavity.

Moraga and Lopez, (2004) performed a numerical analysis of three-dimensional model of mixed convection in an air-cooled cavity in order to compare the variations in different properties with the results of two-dimensional

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models. Wang and Chen, (2002) analyzed forced convection in a wavy-wall channel and demonstrated the effects of wavy geometry, Reynolds number and Prandtl number on the skin friction and Nusselt number. Their results have illustrated that the amplitudes of skin friction coefficient and Nusselt number had increased with an increase in the amplitude to wavelength ratio.

In another study in the same year, Abu-Nada *et al.*, (2010) investigated the effects of variable properties of Al2O3 ewater and CuO ewater nanofluids on the natural convection heat transfer in rectangular enclosures. They observed that at high Rayleigh numbers the viscosity model had a higher impact on the average Nusselt number than the thermal conductivity model. Results of a numerical study on mixed convection in a lid-driven nanofluid filled square cavity with cold side and top wall and a constant heat flux heater on the bottom wall and moving lid were reported by Mansuor *et al.*, (2010).

The effects of Reynolds number, type of nanofluids, size and location of the heater and the volume fraction of the nanoparticles were considered in their study. Their results showed that the rate of heat transfer increased with increase in the length of the heater, Reynolds number and the nanoparticles volume fraction. Ghasemi and Aminossadati, (2010) studied mixed convection of Al2O3ewater nanofluid inside a right triangular cavity with insulated horizontal wall, hot inclined wall and moving cold vertical wall. They considered effects of Richardson number, nanoparticles volume fraction and two different upward and downward movement of the cold vertical wall. Their results showed that addition of the nanoparticles enhanced the rate of heat transfer for all values of Richardson number and for each direction of the sliding wall motion.

Moreover they found a stronger flow circulation within the cavity for downward motion of the cold wall. Mahmoodi, (2011) investigated numerically mixed convection of Al2O3-water nanofluid in rectangular cavities with hot moving bottom lid and cold right, left, and top walls.

PROBLEM DEFINITION AND MATHEMATIC FORMULATION

A schematic view of the square cavity with boundary conditions considered in the present study is shown in Figure 1.

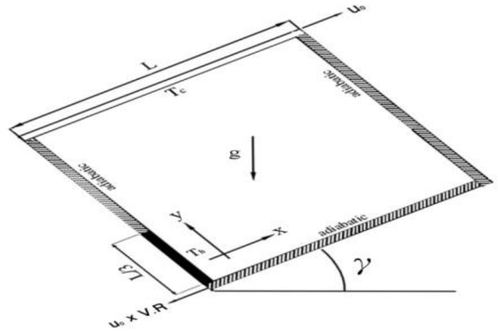

Figure 1: Schematic diagram of physical system

The length of the cavity perpendicular to its plane is assumed to be long enough; hence the problem is considered two dimensional. The cavity is filled with Al2O3ewater nanofluid. The thermophysical properties of nanoparticles and the water as the base fluid at T=25⁰C are used in this study. The nanofluid is considered Newtonian and incompressible and the nanofluid flow is assumed to be laminar. The governing equations for a steady, two-dimensional laminar and incompressible flow are expressed as:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x}+\upsilon_{nf}\nabla^2 u+\frac{(\rho\beta)_{nf}}{\rho_{nf}}g\,\Delta T\,Sin(\gamma), \qquad (2)$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y}+\upsilon_{nf}\nabla^2 v+\frac{(\rho\beta)_{nf}}{\rho_{nf}}g\,\Delta T\,Cos(\gamma) \qquad (3)$$

And

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\nabla^2 T. \qquad (4)$$

The dimensionless parameters may be presented as

$$X=\frac{x}{L},\quad Y=\frac{y}{L},\quad V=\frac{v}{U_0},\quad U=\frac{u}{U_0}$$
$$\Delta T=T_h-T_c,\quad \theta=\frac{T-T_c}{\Delta T},\quad P=\frac{p}{\rho_{nf}U_0^2}. \qquad (5)$$

Hence,

$$\mathrm{Re}=\frac{\rho_f U_0 L}{\mu_f},\quad Ri=\frac{Ra}{\mathrm{Pr}.\mathrm{Re}^2}, \qquad (6)$$
$$Ra=\frac{g\,\mathrm{B}_f\,\Delta T L^3}{\upsilon_f\,\alpha_f},\quad \mathrm{Pr}=\frac{\upsilon_f}{\alpha_f}.$$

The dimensionless forms of the above governing equations (1) to (4) become:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \qquad (7)$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\frac{\upsilon_{nf}}{\upsilon_f}\frac{1}{\mathrm{Re}}.\nabla^2 U+\frac{Ri}{\mathrm{Pr}}.\frac{\beta_{nf}}{\beta_f}\Delta\theta Sin(\gamma) \qquad (8)$$

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\frac{\upsilon_{nf}}{\upsilon_f}\frac{1}{\mathrm{Re}}.\nabla^2 V+\frac{Ri}{\mathrm{Pr}}.\frac{\beta_{nf}}{\beta_f}\Delta\theta Cos(\gamma) \qquad (9)$$

$$U\frac{\partial\theta}{\partial X}+V\frac{\partial\theta}{\partial Y}=\frac{\alpha_{nf}}{\alpha_f}\nabla^2\theta \qquad (10)$$

Thermal diffusivity and effective density of the nanofluid are:

$$\alpha_{nf} = \frac{k_{nf}}{(\rho c_p)_{nf}} \tag{11}$$

$$\rho_{nf} = \varphi \rho_s + (1-\varphi)\rho_f \tag{12}$$

Heat capacity and thermal expansion coefficient of the nanofluid are therefore:

$$(\rho c_p)_{nf} = \varphi(\rho c_p)_s + (1-\varphi)(\rho c_p)_f \tag{13}$$

$$(\rho \beta)_{nf} = \varphi(\rho \beta)_s + (1-\varphi)(\rho \beta)_f \tag{14}$$

The effective viscosity of nanofluid was proposed by Brinkman (1952). as below:

$$\mu_{nf} = \frac{\mu_f}{(1-\varphi)^{2.5}} \tag{15}$$

The effective thermal conductivity of the nanofluid is calculated by the Maxwell model (1904) which is:

$$\frac{k_{nf}}{k_f} = \frac{k_s + 2k_f - 2\varphi(k_f - k_s)}{k_s + 2k_f + \varphi(k_f - k_s)} \tag{16}$$

NUMERICAL METHOD

The set of governing equations associated with the boundary conditions are solved using the finite volume method. In order to couple the velocity field and pressure in the momentum equations, the SIMPLER algorithm is adopted based on a staggered grid system (Mahmoodi, (2011). The hybrid-scheme, which is a combination of the central difference scheme and the upwind scheme, is used to discretize the convection terms while the second order central difference scheme is used to discretize the diffusion terms. To verify grid independence, nine different grid sizes are tested from 21 ×21, 31×31, 41×41, 51×51, 61×61, 71×71, 81×81, 91×91 and 101×101. Average Nusselt number of the hot wall and velocity components in X direction is obtained. It is found that a 81 × 81 uniform grid size, is enough to acquire numerical solution.

RESULTS AND DISCUSSION

Mixed convection in an inclined two-sided lid-driven square cavity subjected to a nanofluid is numerically investigated. The physical model and the coordinate system considered in the investigation are shown in Figure 1. There is a constant length of the heating portion along the hot wall. The remaining portions are adiabatic while partially heating the left wall.

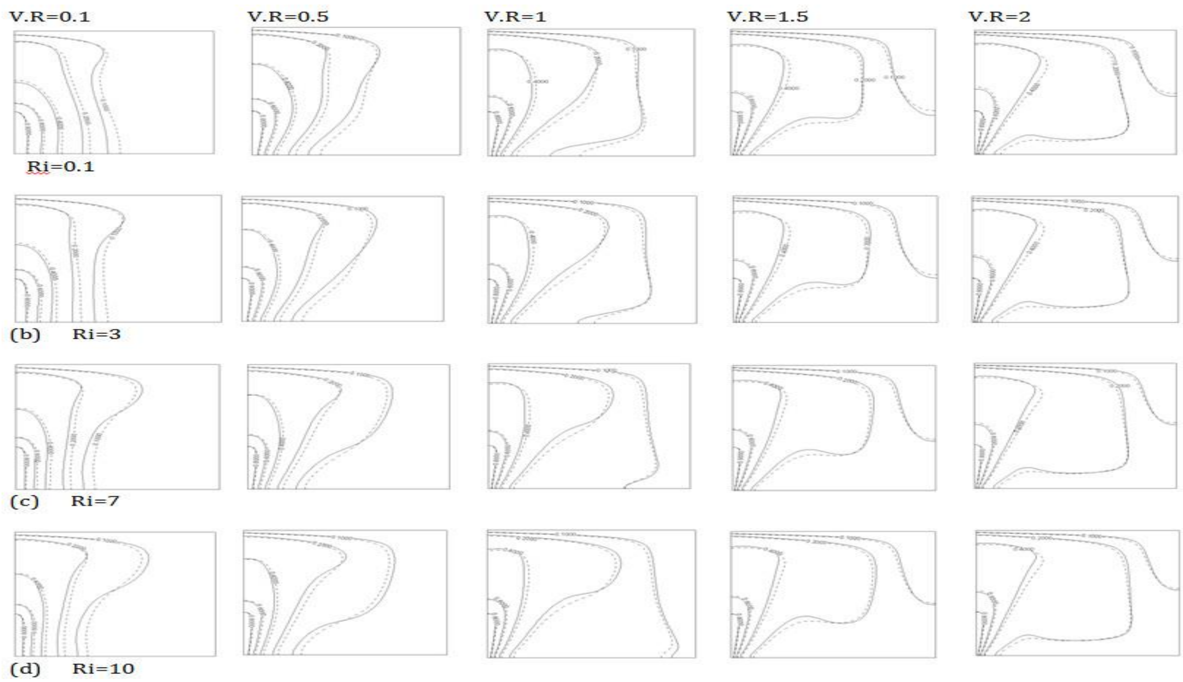

Figure 2: (a)–(d) exhibits isotherms for different velocity ratios and the Richardson numbers with Re=10 and γ =0. Figure 2 (a) shows the temperature distributions for different velocity ratios with Ri =0.1. The isotherms are merely distributed left half of the enclosure for Ri = 0.1 and V. R= 0.1. The same behavior of heat distribution over the enclosure appears even at V. R = 0.5.

The isotherms show that the temperature distributions move slowly to the right wall when the velocity ratio is increased from 0.5 to up. It reveals that the entire enclosure is almost uniformly occupied by isotherms of temperature variations. The isotherms for Richardson numbers of 3, 7 and 10 that show in Figure 2(b) - (d), are largely similar to Figure 2(a). The dashed lines in Figure 2 represent the isotherms for the square cavity including nanofluids with $\varphi = 6\%$. The fluid in the square cavity is a water-based nanofluid containing Al_2o_3 nanoparticles. It is clearly observed from Figure 2 that adding nanoparticles to the base fluid doesn't provide considerable difference in isotherms and temperature variations still retain its overall shape. It is evident from Figure 2 that the heat energy is well distributed from both walls for V. R=2 in all of Richardson numbers. Accordingly, heat transfer increases as the velocity ratio increases.

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