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ORIGINAL ARTICLE

ANALYSIS OF CONVECTION IN AN INCLINED SQUARE ENCLOSURE WITH TWO MOVING LIDS SUBJECTED TO NANOFLUID

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ABSTRACT: In this paper, natural and forced convection heat transfer in a square enclosure is investigated. The top and bottom walls of the mentioned cavity are insulated while the right and left walls are exposed to a constant temperature. The cavity is filled with a nanofluid composed of a mixture of water and Al2O3 spherical nanoparticles. The nanofluid is assumed to be incompressible. Then nanoparticles are presumed to be in thermal equilibrium with the water and there is no slip between them.

KEYWORDS: Streamline, Fluid Flow, Heat Transfer, Mixed Convection.

INTRODUCTION

It is significant from both theoretical and practical point of view that, mixed convection problem with lid-driven flows in enclosures are confronted in a number of engineering applications such as cooling of electronic devices, lubrication technologies, chemical processing equipment, drying technologies, etc. Suspending metallic nanoparticles in fluids is an innovative technique to enhance the thermal conductivities. This suspension would result in considerably larger thermal conductivity in comparison with conventional fluids. These nanoparticles significantly enhance the effective thermal conductivity and subsequently increase the heat transfer characteristics.

The two dimensional flow is characterized by the vortices that are initiated by the existence of buoyancy effect was concluded by Hussein and Hussain, (2010). Mahmoudi *et al.,* (2010) found that the average Nusselt number surged linearly with the increasing solid volume fraction of nanoparticles with fixed heat source geometry and a given Rayleigh number. Sivasankaran *et al.,* (2010) observed that the average Nusselt number enhanced at first and then reduced when increasing the phase deviation from 0 to π. Bilgen and Oztop, (2005) studied partially inclined open square cavities, which were formed by adiabatic walls and a partial opening. Abu-Nada and Chamkha, (2010) showed that adding of Al_2O_3 nanoparticles resulted in improved heat transfer by keeping modest and higher Ra in the enclosure.

Tiwari and Das, (2007) concluded that for the governing parameters Ri and χ the nanoparticles when immersed in a fluid were able to enhance the heat transfer capacity of base fluid. Koca, (2008) showed that the heat transfer improved as the Ra number increased. Jahanshahi *et al.,* (2010) concluded that the indecision associated with different formulas used for the effective thermal conductivity of the nanofluid had a great effect on the natural convection heat transfer characteristics in the enclosure. Shahi *et al.,* (2010) concluded that at a lower Re, higher effect of Richardson number was observed on the average bulk temperature.

Sharif, (2007) numerically studied laminar mixed heat convection in two-dimensional shallow rectangular driven cavities of aspect ratio 10. Some minor vortices are also formed in the cavity for Ri < 1. The local Nusselt number at the heated moving lid starts with a high value and decreases rapidly and monotonically to a small one towards the right side. Many cavity problems studied in literature have constant wall temperature accompanied by insulated walls (vertical or horizontal walls)(Varol *et al.,* 2009; Sivasankaran *et al.,* 2010); these conditions can only be obtained if evaporation or condensation takes place on the wall's surfaces (on constant temperature walls), but in real problem reaching these aims is a bit far from reality.

Guo and Sharif, (2004) carried out a numerical simulation to survey the mixed convection in cavity at different aspect ratios with moving sidewalls and constant heat flux source .Their obtained finding indicate that the average Nusselt number enhanced by moving the heat source towards the sidewalls. A numerical study

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of the mixed convection flow and heat transfer performance of nanofluid in a lid-driven cavity has been executed by Muthtamilselvan *et al.*, (2010). In another study, Talebi *et al.*, (2010) performed a numerical investigation of the mixed convection flows in a square lid-driven cavity using Cu–water nanofluid. Enclosure's horizontal walls were kept while its insulated sidewalls were differentially heated.

Abdelkhalek, (2008) discussed mixed convection in a square cavity by a perturbation technique. Waheed, (2009) studied mixed convective heat transfer in cavities driven by a continuously moving horizontal plate. Very recently Mahmoodi, (2011) carried out a numerical study on mixed convection in lid driven rectangular cavities based on the finite volume method and simpler algorithm.

SCHEMATIC DIAGRAM AND GOVERNING EQUATIONS

A schematic view of the cavity with wavy side walls is depicted in Figure 1. The length of the cavity perpendicular to its plane is assumed to be long enough hence the problem is considered two-dimensional.

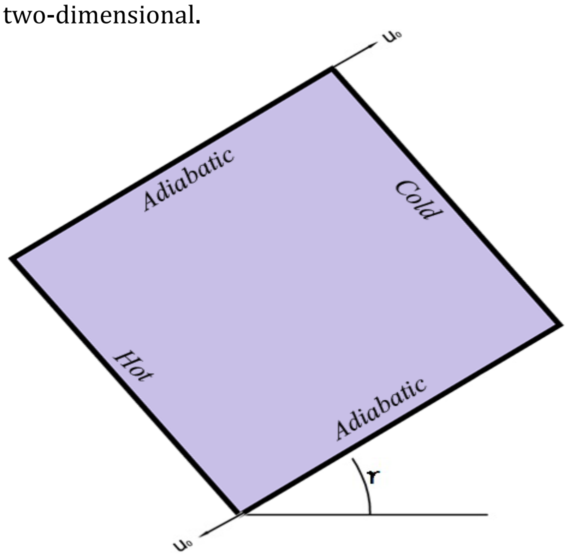

Figure 1: Schematic diagram of current study

The cavity is filled with a nanofluid composed of a mixture of water and Al_2O_3 spherical nanoparticles. The nanofluid is assumed to be incompressible. Then nanoparticles are presumed to be in thermal equilibrium with the water and there is no slip between them. The thermophysical properties of the base fluid and the nano- particles are presented in Table 1. The nanofluid properties are assumed to be constant with the exception of the density which varies according to the Boussinesq approximation.

The governing equations for a steady, two-dimensional laminar and incompressible flow are expressed as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0, \tag{1}$$

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

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

And

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

The dimensionless parameters may be presented as

$$X=\frac{x}{L},\ Y=\frac{y}{L},\ V=\frac{v}{u_0},\ U=\frac{u}{u_0}$$
$$\Delta T=T_h-T_c,\ \theta=\frac{T-T_c}{\Delta T},\ P=\frac{p}{\rho_{nf}u_0^2}. \tag{5}$$

Hence,

$$\mathrm{Re}=\frac{\rho_f u_0 L}{\mu_f},\ Ri=\frac{Ra}{\mathrm{Pr}.\mathrm{Re}^2},\ Ra=\frac{g\beta_f\Delta TL^3}{\upsilon_f\alpha_f},\ \mathrm{Pr}=\frac{\upsilon_f}{\alpha_f}. \tag{6}$$

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

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{7}$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\frac{\upsilon_{nf}}{\upsilon_f}\frac{1}{\mathrm{Re}}.\nabla^2 U \tag{8}$$

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

and

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

2.1. Thermal diffusivity and effective density

Thermal diffusivity and effective density of the nanofluid are

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

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

2.2. Heat capacity and thermal expansion coefficient

Heat capacity and thermal expansion coefficient of the nanofluid are therefore

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

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

NUMERICAL APPROACH

The governing equations are discretized using the finite volume method. The coupling between the pressure and the velocity is done using the SIMPLER algorithm. The diffusion terms in the equations are discretized by a second order central difference scheme while a hybrid scheme (a combination of the central difference scheme and the upwind scheme) is employed to approximate the convection terms. The set of discretized equations are solved by TDMA line by line method. The solution procedure is repeated until the following convergence criterion is satisfied.

$$error = \frac{\sum_{j=1}^{j=M}\sum_{i=1}^{i=N}\left|\lambda^{n+1}-\lambda^{n}\right|}{\sum_{j=1}^{j=M}\sum_{i=1}^{i=N}\left|\lambda^{n+1}\right|} < 10^{-7} \quad (15)$$

Here, M and N correspond to the number of grid points in x and y directions; respectively, n is the number of iteration and λ denotes any scalar transport quantity. To verify grid independence, numerical procedure was carried out for nine different mesh sizes, namely; 21 × 21, 31 × 31, 41 × 41, 51 × 51, 61 × 61, 71 × 71, 81 × 81, 91 × 91 and 101 × 101. Average Nu of the left hot wall is obtained for each grid size.
an 81 × 81 uniform grid size yields the required accuracy and was hence applied for all simulation exercises in this work as presented in the following section.

RESULTS AND DISCUSSION

In this paper, natural and forced convection heat transfer in a square enclosure is investigated. The top and bottom walls of the mentioned cavity are insulated while the right and left walls are exposed to a constant temperature.
Figure 2 illustrates streamlines and isotherms for Ri=10, T=300K, R=0.07 and inclination angle of 60˚. In this figure, the effect of diameter of nanoparticles on the mixed convection inside the cavity is investigated. The Richardson number is kept constant and the diameter is varying from 15 to 100nm. It is evident that an increase in nanoparticle diameter influences the flow pattern and isotherm contours inside the cavity relatively.
In this figure, conduction heat transfer is not strong and the heat transfer occurs mainly through convection. As the diameter increases, the forced convection becomes stronger. As can be seen from the figure with increase in the diameter the concentration of the isotherms in the side walls, especially the wall in temperature distribution, augments.

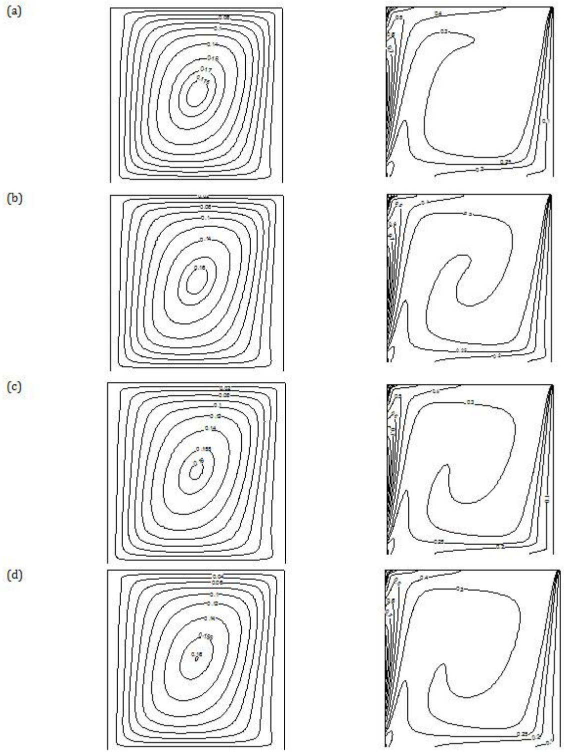

Figure 2: Streamlines (on the left) and isotherms (on the right) for Ri=10, T=300K, R=0.07 and inclination angle of 60˚ with different value of dp: (a) 15nm, (b) 40nm, (c) 70nm, (d) 100nm.

It is because of increase in thermal conductivity of the nanofluid which results in enhancement of diffusion of heat. Moreover it can be seen than when the dp increases, the core of the eddy becomes gradually smaller. With enhancing of the diameter, an augmentation in the value of dimensionless stream function is observed.

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