JOURNAL OF CURRENT RESEARCH IN SCIENCE (ISSN 2322-5009)
2013, Vol. 1, No. 3, pp:164-168
Available at www.jcrs010.com

ORIGINAL ARTICLE

COMBINED CONVECTION FLOW IN A LID-DRIVEN SQUARE CAVITY SUBJECTED TO A VARIABLE PROPERTIES OF NANOFLUID: EFFECT OF REYNOLDS NUMBER

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ABSTRACT: This study is focused on mixed convection of nanofluid in the lid- driven cavity using new variable properties formulation. In the present investigation we examine the effects of Reynolds number on hydrodynamic and thermal characteristics.
KEYWORDS: nanofluid, mixed convection, Reynolds number, Heat transfer.

INTRODUCTION

One of the most significant scientific challenges in the industrial area is cooling, which applies to many diverse productions, including microelectronics, transportation and manufacturing. Technological developments such as microelectronic devices operating at high speeds, higher-power engines, and brighter optical devices are driving increased thermal loads, requiring advances in cooling. The conventional method for increasing heat dissipation is to increase the area available for exchanging heat to use a better heat conductive fluid. However, this approach involves an undesirable increase in the size of a thermal management system; therefore, there is an urgent need for new and novel coolants with improved performance. The innovative concept of 'nanofluids' heat transfer fluids consisting of suspended of nanoparticles – has been proposed as a prospect for these challenges (Keblinski *et al.*, 2005).

Nanofluid is a dispersion mixture in which nanoparticles are uniformly and stable suspended in a base fluid. Due to the presence of these particles on the base fluid, heat transfer rate can be improved because the thermal conductivity of these particles is higher than the base fluid (Choi *et al.*, 2004). Many researchers have examined various aspects of nanofluids. Several investigates on mixed convection in single or double lid-driven enclosure flow and heat transfer including different cavity geometries and configurations, different base fluids and boundary condition have been reported (Zarei *et al.*, 2013; Abbasian Arani *et al.*, 2012; Hemmat Esfe, 2013).

Effect of existence on obstacles within the cavity is one of the interesting investigations for researchers. Recently free convection fluid flow and heat transfer investigated numerically by Mazrouei Sebdani *et al.*, (2012). Their work was included of Cu-water nanofluid around the adiabatic square bodies at the center of a square cavity. They illustrated that for most Rayleigh numbers the Nusselt number increases with increase in the volume fraction of the nanoparticles. They also showed that at low Rayleigh numbers by increasing the size of the adiabatic square body, the rate of heat transfer decreases and opposite is true at high Rayleigh numbers. In this article, the impact Reynolds number on the hydrodynamics and thermal characteristics are discussed.

PHYSICAL MODELING AND FORMULATION

Figure 1 shows a two-dimensional square double lid-driven cavity considered for the present study with physical dimensions. The height and the width of the cavity are denoted by L. The length of the cavity perpendicular to its plane is assumed to be long enough.

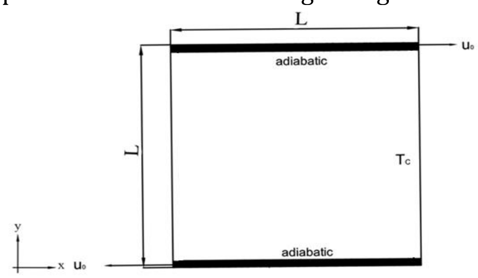

Figure 1: Schematic diagram of the double lid-driven cavity considered in the present study.

The nanofluid in the enclosure is Newtonian, incompressible and laminar. In addition, it is assumed that both the fluid phaseand nanoparticles are in the thermal equilibrium state and they flow with the same velocity. The density variation in the body force term of the momentum equation is satisfied by Boussinesq's approximation. The thermophysical properties

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of nanoparticles and the water as the base fluid at T = 300°K are presented in Table1.

Table 1: Thermophysical properties of water and nanoparticles at T =300°k.

Physical properties	Fluid phase (Water)	Solid (Al_2O_3)
Cp(J/kg k)	4179	765
ρ(kg/m3)	997.1	3970
K (W m-1 K-1)	0.6	25
$\beta\times10^{-5}$ (1/K)	21.	0.85
$\mu\times10^{-4}$(Kg/ms)	8.9	……..

The thermal conductivity and the viscosity of the nanofluid are taken into consideration as variable properties; both of them change with volume fraction and temperature of nanoparticles. Under the above assumptions, the system of governing equations is:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x}+\upsilon_{nf}\nabla^2 u, \quad (2)$$

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

And

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

The dimensionless parameters may be presented as

$$X=\frac{x}{L},\ Y=\frac{y}{L},\ V=\frac{v}{u_0},\ U=\frac{u}{u_0} \quad (5)$$

$$\Delta T=T_h-T_c,\ \theta=\frac{T-T_c}{\Delta T},\ P=\frac{p}{\rho_{nf}u_0^2}.$$

Hence,

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

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

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

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

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

And

(10)

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

2.1. Thermal diffusivity and effective density

Thermal diffusivity and effective density of the nanofluid are

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

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

2.2. Heat capacity and thermal expansion coefficient

Heat capacity and thermal expansion coefficient of the nanofluid are therefore

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

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

2.3. Viscosity

The effective viscosity of nanofluid was calculated by:

$$\mu_{eff}=\mu_f(1+2.5\varphi)\left[1+\eta\left(\frac{d_p}{L}\right)^{-2\varepsilon}\varphi^{2/3}(\varepsilon+1)\right] \quad (15)$$

This well-validated model is presented by Jang *et al.*, (2007) for a fluid containing a dilute suspension of small rigid spherical particles and it accounts for the slip mechanism in nanofluids. The empirical constant ε and η are _0.25 and 280 for Al_2O_3, respectively. It is worth mentioning that the viscosity of the base fluid (water) is considered to vary with temperature and the flowing equation is used to evaluate the viscosity of water.

$$\mu_{H_2O}=(1.2723\times T_{rc}{}^5-8.736\times T_{rc}{}^4+33.708\times T_{rc}{}^3-246.6\times T_{rc}{}^2+518.78\times T_{rc}+1153.9)\times 10^6 \quad (16)$$

Where, $Trc=Log(T-273)$.

2.4. Dimensionless stagnant thermal conductivity:

The effective thermal conductivity of the nanoparticles in the liquid as stationary is calculated by the Hamilton and crosser (H-C model) (Hamilton and Crosser, 1962) which is:

$$\frac{k_{stationary}}{k_f}=\frac{k_s+2k_f-2\varphi(k_f-k_s)}{k_s+2k_f+\varphi(k_f-k_s)} \quad (17)$$

2.5. Total dimensionless thermal conductivity of nanofluids:

$$\frac{k_{nf}}{k_f}=\frac{k_{stationary}}{k_f}+\frac{k_c}{k_f}=\frac{k_s+2k_f-2\varphi(k_f-k_s)}{k_s+2k_f+\varphi(k_f-k_s)}+ c\,\frac{Nu_p d_f\,(2-D_f)D_f}{\Pr(1-D_f)^2}\,\frac{\left[\left(\frac{d_{\max}}{d_{\min}}\right)^{1-Df}-1\right]^2}{\left(\frac{d\max}{d\min}\right)^{2-Df}-1}\,\frac{1}{d_p} \quad (18)$$

This model was proposed by Xu *et al.*, (2006) and it has been chosen in this study to describe the thermal conductivity of nanofluids. c is an empirical constant(e.g. c = 85 for the deionized water and c = 280 for ethylene glycol) but independent of the type of nanoparticles. Nup is the Nusselt number for liquid flowing around a spherical particle and equal to two for a single particle in this work. The fluid molecular diameter $d_f=4.5*10^{-10}$(m) for water in present study. The fractal dimension D_f is determined by:

$$D_f = 2 - \frac{\ln \varphi}{\ln\left(\frac{d_{p,\min}}{d_{p,\max}}\right)}$$

Where, $d_{p,max}$ and $d_{p,min}$ are the maximum and minimum diameters of nanoparticles, respectively. Ratio of minimum to maximum nanoparticles $d_{p,min}/d_{p,max}$ is R.
In this study R is constant and equal to 0.007.

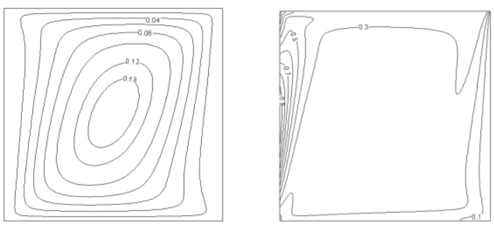
$$d_{p,\max} = d_p \cdot \frac{D_f - 1}{D_f}\left(\frac{d_{p,\min}}{d_{p,\max}}\right)^{-1}$$

$$d_{p,\min} = d_p \cdot \frac{D_f - 1}{D_f}$$

RESULTS AND DISCUSSION

The impact of Al2O3-water nanofluid variable properties on mixed convection flow and heat transfer in a two-sided lid-driven square enclosure and moving horizontal walls was studied numerically using the finite volume method and SIMPLER algorithm.
Results for Re=100 are shown in Figure 2. This figure demonstrates that by increasing the shear force, streamline pattern and the temperature distribution inside the cavity become completely different from that of lesser Reynolds numbers. For this value of Renumber, areas of the thermal boundary layers adjacent to the walls are clearly distinguished and also the central area of the cavity is isothermal. Increasing the volume fraction of nanoparticles causes a decrease in the temperature gradient of the areas close to the walls due to the increase in the amount of heat conduction. Streamlines also show formation of a clockwise vortex which its central area is elliptical form.

A



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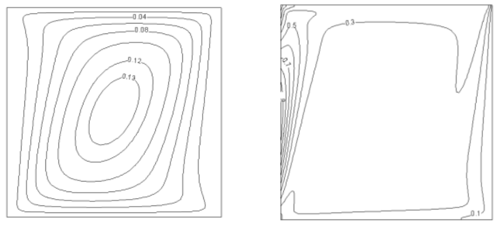

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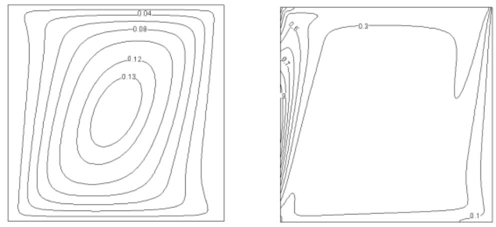

Figure 2: Streamlines (left) and isotherms (right) for Al_2O_3 water nanofluid inside the cavity with $Gr=10^4$, Re=100 for a) φ =0.01 b) φ =0.03 c) φ =0.05.

CONCLUSION

In this paper, thermal characteristics and flow patterns inside a cavity filled with nanofluid were investigated. Code was employed to study the effects of Al_2O_3-water nanofluid variable thermal effective dynamic viscosity and thermal conductivity on isotherm and streamline inside the enclosure and the following results were obtained:
In higher Grashof and Reynolds number, increasing the volume fraction of nanoparticles has significant effect on the streamline pattern and the temperature distribution inside the cavity.

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