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Investigating the Behavior of Nanofluids in a Rectangular Enclosure in Order to Enhance the Heat Transfer Coefficient

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ABSTRACT

Fluids that contain very small suspended particles in nanometer size which are called nanofluids, have a great potential for increasing heat transfer; therefore, this group of fluids have attracted special attention as heat transfer media. In this study, natural convection heat transfer for a few nanofluids are investigated and compared in a two-dimensional cavity using numerical methods. Calculations for Grashof number between 10^3 and 10^5 and the volume fraction of nanoparticles Al_2O_3, Cu and TiO_3 between 0 to 30% are done. Results indicate an increase in the average Nusselt number with nanoparticles volume fraction for all values of the Grashof number. Also, the average Nusselt number for water-Cu nanofluid is more than other nanofluids. Most of the effect nanoparticles is in the fluid transport properties, especially in the heat transfer properties,So nanofluids in heat exchanger, which can lead to significant reductions in fluid flow can be used in Oil & Gas refineries. Finally, the heat exchangers are designed with less weight and size. Also, due to the kinetic energy of particles hitting the surface, creating little Create friction and low wear and less damage to channels and pumps.
KEYWORDS: nanofluid, thermal conductivity, heat transfer, natural convection, numerical study.

INTRODUCTION

Because of its simplicity, low cost, low noise, small size and high reliability, heat transfer via natural convection have been considered by designers as an important phenomenon in cooling mechanisms of engineering systems. Some industries and engineering areas that use natural convection are: thermal insulators, electrical industries, solar collectors and cooling systems of nuclear reactors. Improving heat transfer in these systems is an important issue in terms of optimized energy consumption. Fluids that are normally used for heat transfer, such as water, ethylene glycol and motor oil have relatively low thermal conductivity compared to solids. High thermal conductivity of solid particles can be used to increase the thermal conductivity of fluids. To this end, these particles should be added to fluids. The idea of adding particles in nanometer size (nanoparticles) to the base fluid in order to improve fluid thermal conductivity has recently been proposed [1,2]. The mixture of nanoparticles in base fluid is called nanofluid.

Several experimental, theoretical and numerical studies have been carried out about various aspects of natural convection heat transfer within enclosures with different aspect ratio in the form of two or three dimensions. With Nanofluids being suggested in this area, studies related to their use in the cavity to improve the efficiency of natural convection were also carried out.

Putra et. al [3] in 2003,conducted an experiment to observe natural convection features of water - aluminum oxide nanofluid. They reported that increasing concentration of suspended nanoparticles in the base fluid reduces natural convection heat transfer. This phenomenon is evident in reduced Nusselt number on specified Rayleigh number. However, they did not clearly specify the reason for this behavior. They stated that increased volume fraction increases nanofluid viscosity, while nanofluid maintains its Newtonian behavior.

Khanafer et. al [4] in 2003, in a numerical study investigated nanofluid natural convection within a two-dimensional enclosure. In their numerical model, Brinkman's model is used to estimate the effective viscosity and Wasp model is used to measure thermal conductivity. Compared with Kim's findings, although they use the same model to estimate viscosity and thermal conductivity, their numerical results are different from those of Kim. Moreover, they showed that with increasing nanoparticles volume fraction, the nanofluid velocity components are increased as a result of increased energy transfer. Their study also shows that Nusselt number for nanofluid natural convection increases with increasing volume fraction. These results are consistent with experimental findings of Putra et. al.

Kim et. al [5] in 2004, studied the instability of natural convection under the effect of buoyant force as well as theoretical models used for properties of nanofluids heat transfer. They used Einstein and Brinkman models to estimate the effective viscosity of the nanofluid and used Hamilton-Crosser and Bergman models for nanofluid effective thermal conductivity. However, it is reported that they couldn't estimate nanofluid viscosity and thermal conductivity well.

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Jou and Tzeng [6] in 2006, numerically examined improved heat transfer in an enclosure containing water – Al_2O_3 nanofluid. They confirmed that the rate of nanofluid heat transfer increases with nanoparticles volume fraction and buoyancy parameters.

Nana [7] in 2007, in an experimental study examined Water - Al_2O_3 nanofluid in a two-dimensional cavity. He presented an empirical relationship for Nusselt number as a function of nanoparticles volume fraction and Rayleigh number. He also concluded that increasing heat transfer at low volume fraction nanoparticles is also possible.

Ghasemi and Aminosadati [8], in 2009, used numerical methods to investigate natural convection in a square cavity at various angles relative to the horizon. They used Brinkman model for calculating viscosity and Co and Klinstor for calculating effective thermal conductivity. They concluded that adding CuO nanoparticles to water improves heat transfer. They found that for low Rayleigh numbers where heat transfer through conduction is dominant, changes in cavity angle have no effect on heat transfer. However, for higher Rayleigh numbers like 10^5, maximum heat transfer occurs at a specific angle.

Mansour et. al [9] in 2011, examined natural convection inside a cavity containing water-Cu nanofluid with a heat source on the wall. They investigated the effect of volume fraction, size and location of heat source, and Rayleigh number on flow lines, isotherm lines and velocity profile. They stated that increasing volume fraction increases average Nusselt number across the heat source.

The main objective of this study is to investigate natural convection heat transfer in a closed cavity filled with nanofluid. Three different water-based fluid nanofluids and nanoparticles Al_2O_3, Cu and TiO_3 are used to investigate the effects of nanoparticles on the flow field, temperature distribution and heat transfer. In this study, the nanofluid effective conductivity coefficient is calculated taking into account the scattering effect.

2.Problem definition and mathematical model

In Figure (1), a two-dimensional closed cavity with Height of H and width of L filled with nanofluid is shown. Horizontal walls are insulated and impermeable. The nanofluid inside the cavity is Newtonian and Incompressible. It is assumed that nanoparticles are of the same shape and size. It is also assumed that both phases of fluid and nanoparticles are in thermal equilibrium and have the same flow rate. The vertical wall on the left is hot and its temperature is kept constant at T_H, while the right wall is cold and its temperature its temperature is kept constant at T_L.

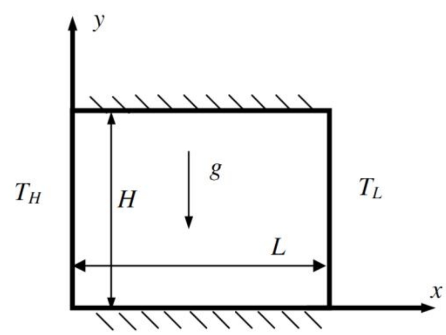

Figure (1)- Schematic for the physical model

In the study of nanofluids convection heat transfer, determining their detailed thermophysical properties is an important issue. Calculating the density and specific heat capacity is relatively simple but there are considerable differences in experimental results and theoretical models for calculating viscosity and thermal conductivity .

Nanofluid density can be obtained from the following equation:

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_p \tag{1}$$

where ϕ is volume fraction of particles and *nf*, *p* and *f* are nanofluid, particles and base fluid respectively. Pak and Cho [10] experimentally demonstrated that Equation (1) is a correct relationship to calculate nanofluid density.

Specific heat is a property based on specific gravity and its effect depends on the nanofluid components density. As a result:

$$C_{p,nf} = (1-\phi)C_{p,f} + \phi C_{p,p} \tag{2}$$

Effective dynamic viscosity of nanofluid consisting of spherical particles is estimated by Brinkman [11] according to the following equation:

$$\mu_{eff} = \frac{\mu_f}{(1-\phi)^{2.5}} \tag{3}$$

Xuan and Roetzel [12], state that thermal dispersion in nanofluid flow occurs due to nanoparticles' random motion. Considering the fact that random motion of particles creates a small perturbation in velocity and temperature, they showed that effective thermal conductivity in the energy equation is as follows.

$$k_{eff} = k_{nf} + k_d \tag{4}$$

In the present study, K_{nf} is calculated as follows based on Maxwell model [13]:

$$k_{nf} = \frac{k_p + 2k_f + 2(k_p - k_f)\phi}{k_p + 2k_f - (k_p - k_f)\phi} k_f \tag{5}$$

k_d is dispersed thermal conductivity and is calculated via the following relationship [12]:

$$k_d = C(\rho C_p)_{nf} \left|\bar{V}\right| \phi d_p \tag{6}$$

where ρ is density, C_p is specific heat capacity, $\left|\bar{V}\right| = \sqrt{u^2 + v^2}$, ϕ is volume fraction of particles, and d_p is the diameter of nanoparticles. C is an empirical constant obtained via compatibility with experimental results.

Based on thermophysical properties mentioned and the following dimensionless parameters,

$$U = \frac{u}{\sqrt{g\beta_f H \Delta T}} \qquad V = \frac{v}{\sqrt{g\beta_f H \Delta T}} \qquad \theta = \frac{T - T_L}{T_H - T_L}$$

$$\mathrm{P} = \frac{pH^2}{\rho\alpha^2} \qquad X = \frac{x}{H} \qquad Y = \frac{y}{H}$$

$$\mathrm{Gr} = \frac{g\beta_f \Delta T H^3}{\upsilon_f^{\,2}} \qquad \mathrm{Pr} = \frac{\alpha_f}{\upsilon_f} \qquad \mathrm{Ra} = \mathrm{Gr}\,\mathrm{Pr}$$

The dimensionless form of equations dominating nanofluid natural convection inside a closed cavity is as follows. It uses the Boussinesq approximation in which the fluid properties except for fluid density in terms of volumetric power in the momentum equation is considered constant.

Continuity equation:

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

X-Momentum equation:

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial \mathrm{P}}{\partial X} + \frac{\mu_{eff}}{\rho_{nf}} \nabla^2 U \tag{8}$$

Y-Momentum equation:

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial \mathrm{P}}{\partial Y} + \frac{\mu_{eff}}{\rho_{nf}} \nabla^2 V + \frac{1}{\rho_{nf}}[(1-\phi)(\rho\beta)_f + \phi(\rho\beta)_s]g\theta \tag{9}$$

Energy equation:

$$U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{1}{\mathrm{Pr}\sqrt{\mathrm{Gr}}}\left[\frac{\partial}{\partial X}\left(\chi\frac{\partial \theta}{\partial X}\right) + \frac{\partial \theta}{\partial Y}\left(\chi\frac{\partial \theta}{\partial Y}\right)\right] \tag{10}$$

χ in the energy equation is:

$$\chi = \frac{\left[\frac{k_{nf}}{k_f}\right]}{(1-\phi) + \phi\frac{(\rho C_p)_s}{(\rho C_p)_f}} + C\phi\frac{d_p}{H}\mathrm{Pr}\sqrt{\mathrm{Gr}}\sqrt{U^2 + V^2} \tag{11}$$

In the above equations Gr is the Grashof number and Pr is Prandtl number. In this study, particle diameter is 10 nm, cavity length to width ratio is one and cavity height equals 1 cm.

3.Numerical procedure

FLUENT Software is used to solve this problem. Momentum and energy equations are made discrete with Upwind second-order method and the pressure equation is made discrete with PRESTO method. They are then solved using SIMPLEC algorithm. Considering 10^{-6} as the as the criterion for convergence in continuity, momentum and energy equations, the solution will converge after 550 iterations.

To ensure the independence of solutions on grid size, the results are compared for the four grid size in Figure (2). In this figure, the horizontal dimensionless speed on line x=L/2 for quantities of dimensionless Y is plotted for different networks. On this basis, a grid with 81 × 81 size with a density near the wall is selected.

To ensure the accuracy of modeling, the results obtained are compared with the experimental results mentioned in reference [14]. The fluid used in empirical work is air with Prandtl number 0.71 and the Rayleigh number 1.89×10^{5}. Other flow characteristics are given in Table 1.

Table 1- Thermophysical properties of air

Density (kg/m^3)	1.127
Specific heat (J/kgK)	1.007×10^{3}
Thermal conductivity (W/mK)	2.710×10^{-2}
Thermal expansion coefficient (1/K)	6.092×10^{-3}
Viscosity (Pa s)	1.911×10^{-5}
Gr	2.662×10^{5}
Pr	7.100×10^{-1}
Ra	1.890×10^{5}

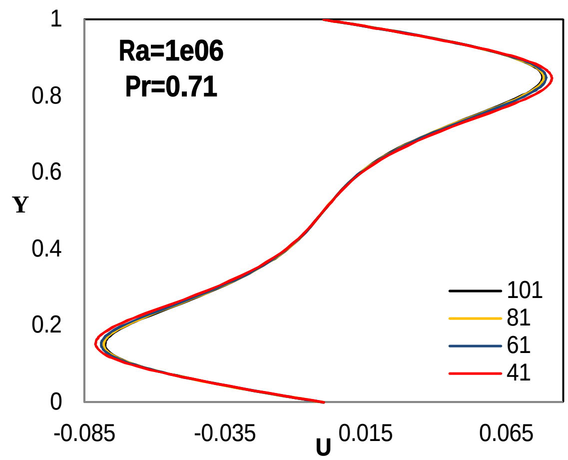

Figure (2)- Horizontal velocity profiles at mid-sections of the cavity for various mesh sizes

In Figures (3) and (4), the temperature profile and vertical velocity profile in the middle line of cavity, obtained from modeling, are compared with Krane and Jessee's experimental work [14]. As can be seen, the modeling results match well with experimental results.

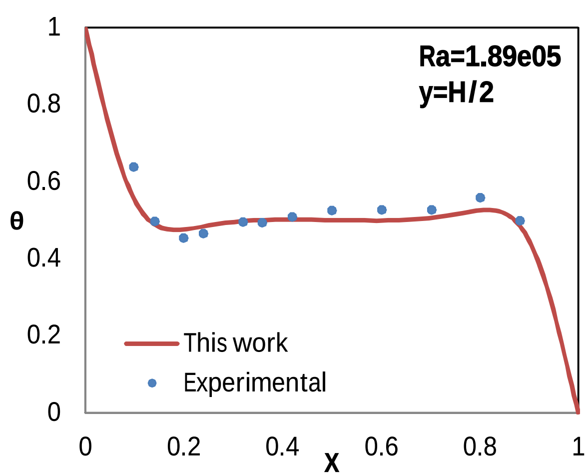

Figure (3)- Comparison of the temperature profiles between the present results and the experimental results by Krane and Jessee (Ra=1.890×10^{5} , Pr=0.71)

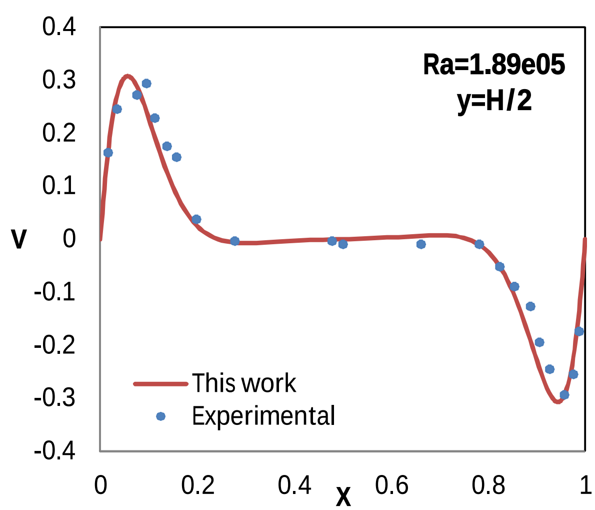

Figure (4)- Comparison of the vertical velocity profiles between the present results and the experimental results by Krane and Jessee (Ra=1.890×10^{5} , Pr=0.71)

4. RESULT AND DISCUSSION

After ensuring the accuracy of numerical modeling, in this section characteristics of natural convection heat transfer for nanofluids of water-Cu, water-Al_2O_3 and water-TiO_3 are compared. The thermophysical characteristics of these nanofluids at room temperature are shown in table 2.

In figure (5) the effects of adding nanoparticles to the base fluid in different volume fractions on the flow lines for water-Cu nanofluid and Grashof numbers 10^3, 10^4 and 10^5, are shown. In the absence of nanoparticles and for low Grashof number ($Gr=10^3$) a vortex in the center of the cavity appears as a dominant characteristic of the fluid flow. With increasing Grashof number in this case ($\varphi = 0$) the core vortex tends to become elliptic for $Gr=10^4$ and then break into three vortexes for the Grashof number $Gr = 10^5$. In each of these cases, the flow line intensity increases with an increase in nanoparticles volume fraction as a result of increased energy transfer and irregular motion of nanoparticles.

Furthermore, at the Grashof number $Gr = 10^{5,}$ the flow lines core vortex start rotating clockwise as a result of increasing volume fraction.

Increasing volume fraction leads to an increased velocity in the center of cavity due to greater heat transfer between the solid-fluid. Isothermal lines in Figure (6) show that increasing volume fraction for higher Grashof number separates vertical thermal layers. This is due to multiple influences from factors such as gravity, Brownian motion, layering at the liquid-solid interface, nanoparticle clustering and the scattering effect. In this study, only the scattering effect is considered. For a pure fluid, isothermal lines in the cavity center is horizontal and only near the wall and inside the heat boundary layers it is vertical. With increasing nanoparticles volume fraction, isothermal lines in the cavity center tend to become vertical. This shows an increase in heat transfer rate due to temperature gradient as a result of presence of more nanoparticles in the fluid.

The counter of increase in effective thermal conductivity of water-Cu nanofluid within the cavity for volume fraction and different Grashof numbers is shown in Figure (7). This Figure shows a significant increase in effective thermal conductivity of nanofluid compared to effective thermal conductivity of the pure fluid $\left((k_{eff,nf} - k_f)/k_f\right)$. In these figures, the differences in the effective thermal conductivity within the cavity are due to the scattering effect which, considering the relation (6), depends on nanofluid velocity. Increasing the amount of volume fraction of nanoparticles significantly increases thermal conductivity.

Table 2- Thermophysical properties of fluid and nanoparticles

Physical properties	Fluid phase (water)	Cu	Al_2O_3	TiO_3
Cp (J/kg.K)	4179	385	765	686.2
ρ (kg/m^3)	997.1	8933	3970	4250
K (W/m.K)	0.613	400	40	8.9538
$\alpha\times10^7$ (m^2/s)	1.47	1163.1	131.7	30.7
$\beta\times10^5$ (1/K)	21	1.67	0.85	0.9

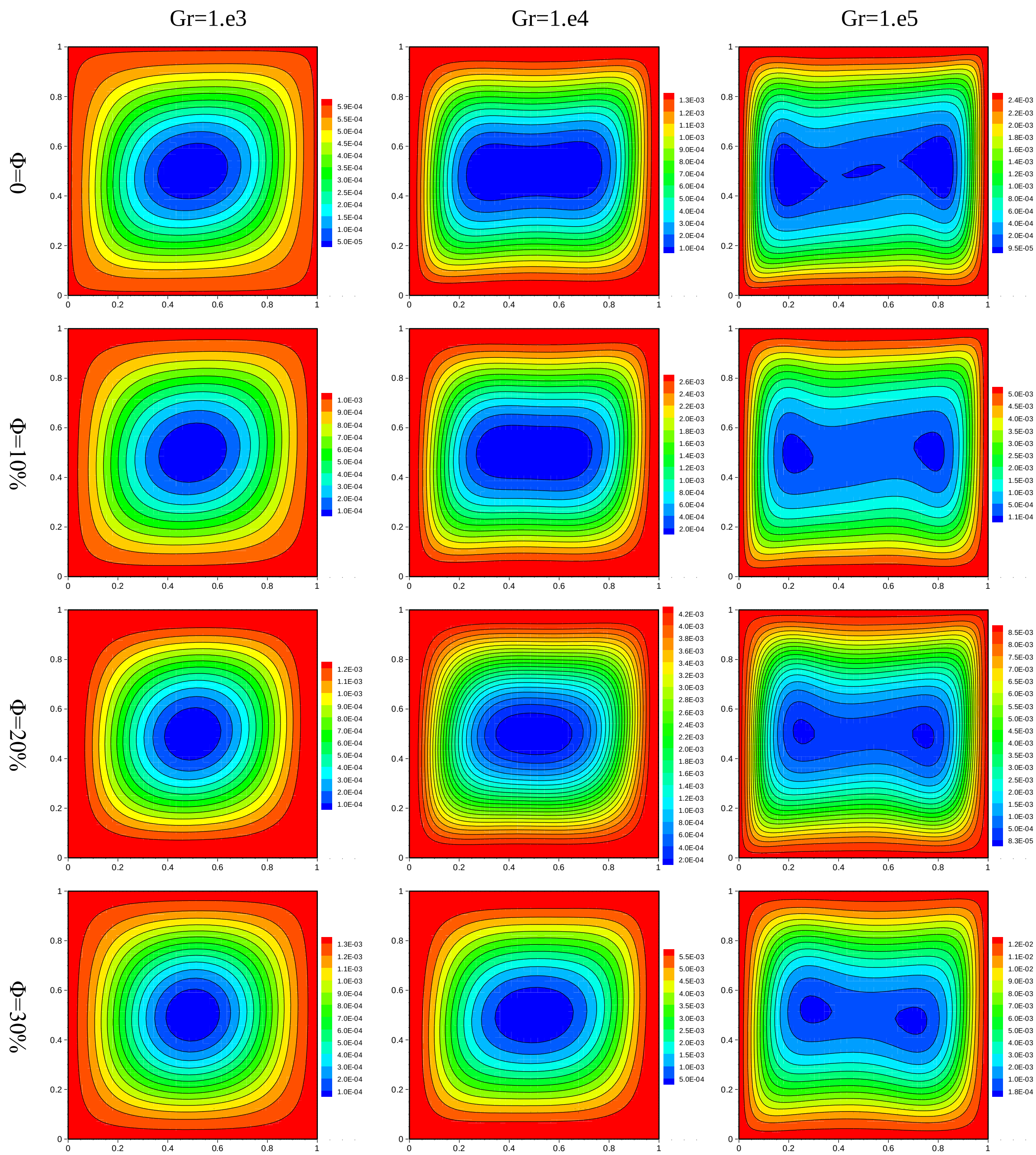

Figure (5)- Streamlines contours for Cu-water nanofluids at varios Grashof numbers and volume fraction

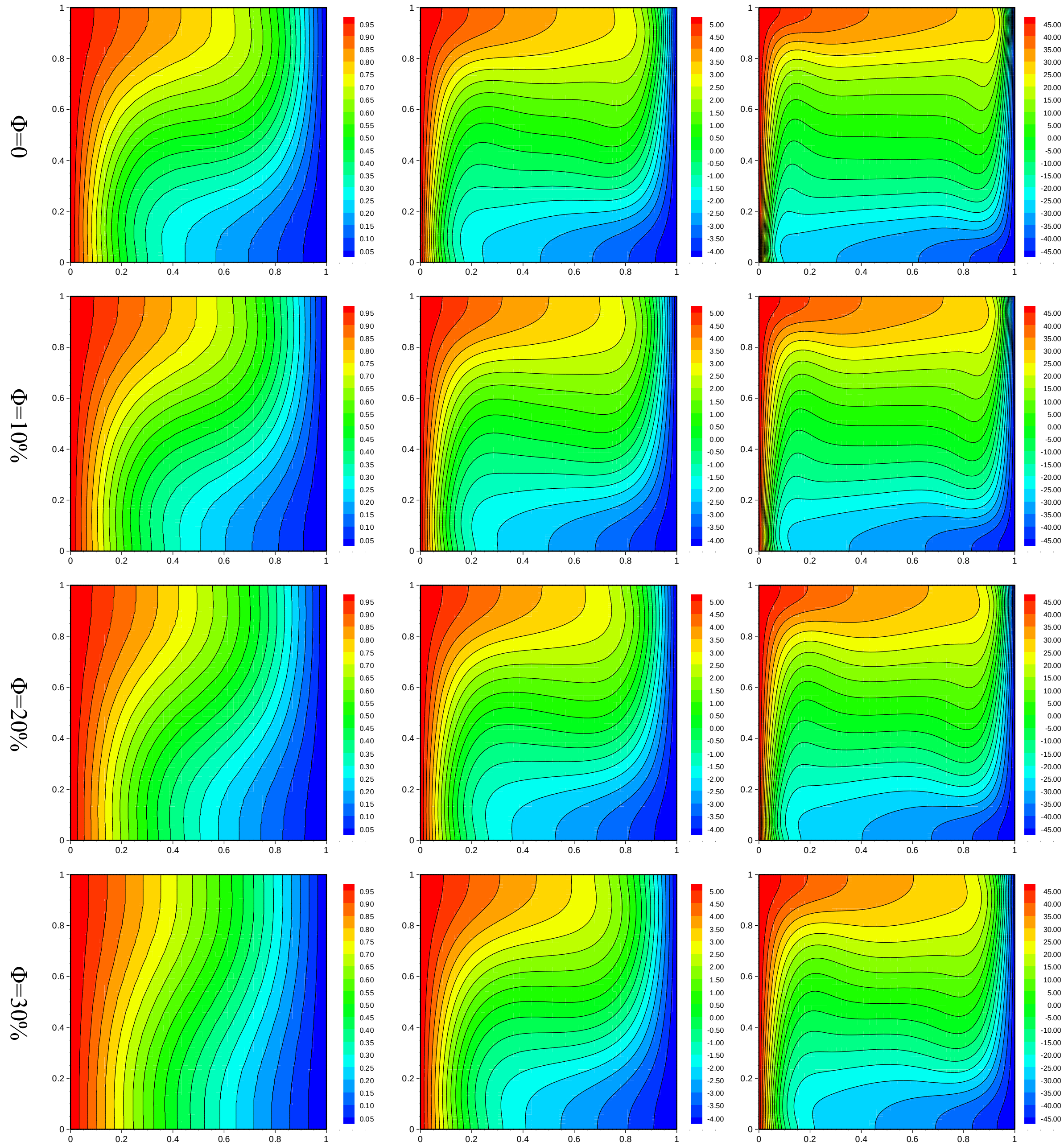

Figure (6)- Isotherms plots for Cu-water nanofluids at varios Grashof numbers and volume fraction

In Figure (8), average Nusselt number on hot wall based on Grashof number and the particle volume fraction for water-Cu, water-Al_2O_3 and water-TiO_3 are shown. This figure shows the relatively linear changes in Nusselt number with the volume fraction for different nanofluids. It is noteworthy that the change process of Nusselt number in this figure is based on thermal conductivity of base fluid (water). If the Nusselt number is calculated based on the nanofluid effective thermal conductivity, the changes will go down. As can be seen, with increasing volume fraction for all Grashof numbers and nanofluids, the Nusselt number and as a result heat transfer increases. The increase is higher for water-Cu and water - aluminum oxide than it is for water - titanium oxide nanofluid, particularly for higher Grashof numbers. At higher Grashof numbers, due to greater effects of thermal dispersion caused by higher fluid vortex, increasing volume fraction of nanoparticles increases the effective conductivity coefficient much higher than the case of lower Grashof number.

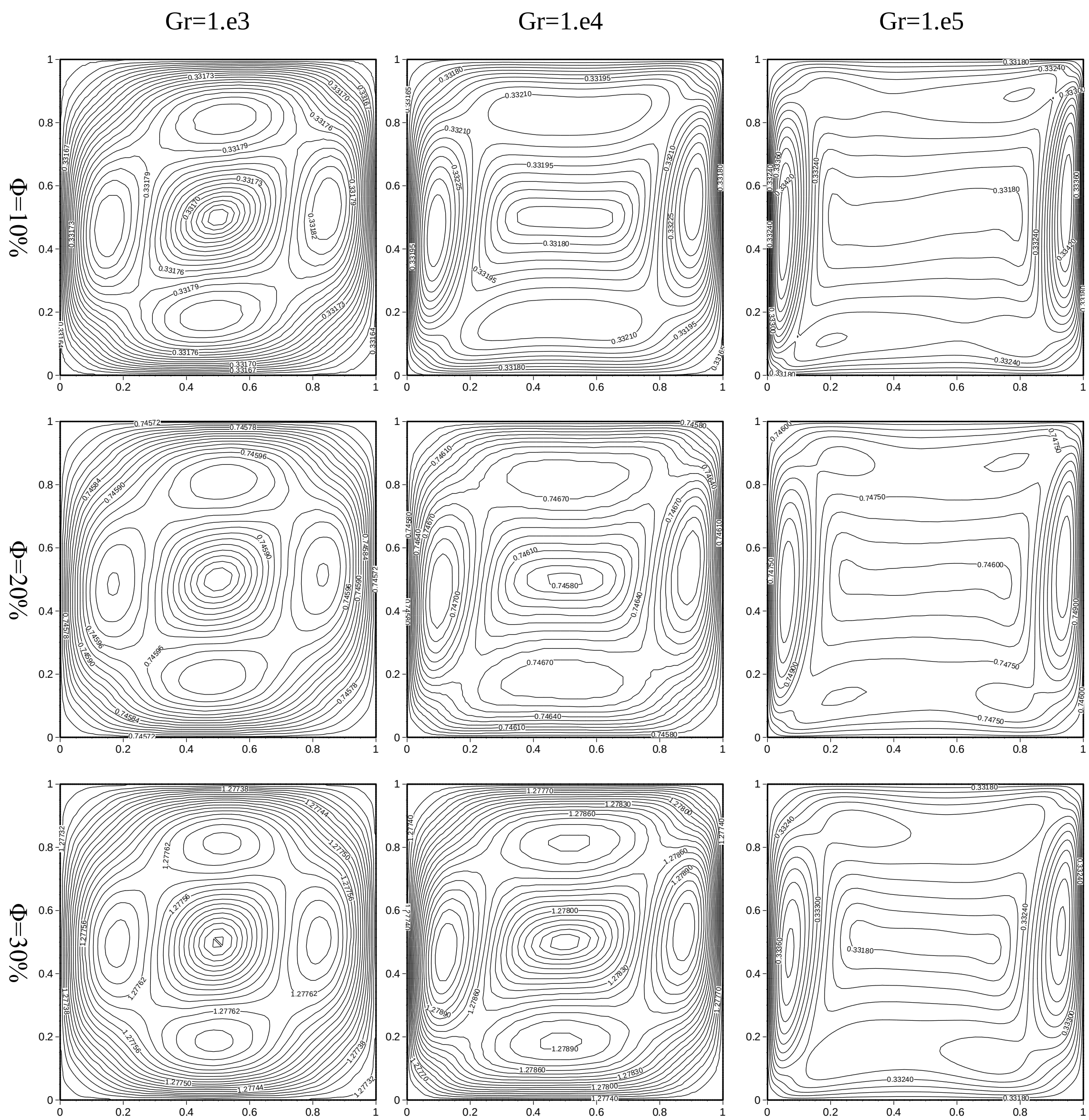

Figure (7)- Effective thermal conductivity enhancement contours for various volume fractions

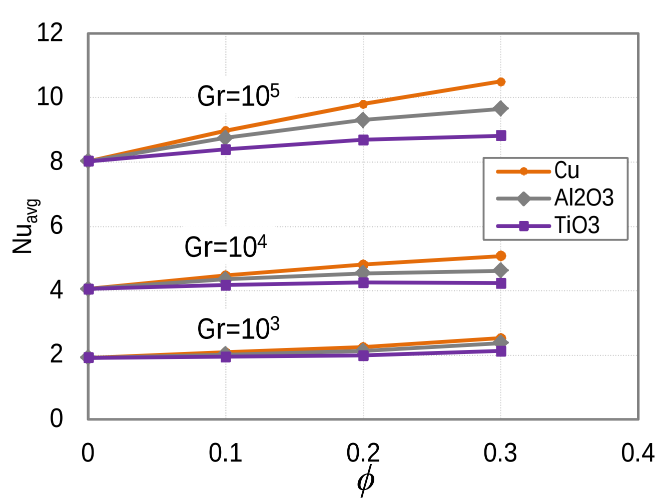

Figure (8)- Average Nusselt number

As a result, the slope of average Nusselt number in terms of volume fraction is higher for higher Grashof numbers.
Figures (9) to (11) show the effects of Grashof number and volume fraction on velocity and temperature profiles in the mid-line of cavity for water-Cu nanofluid. The numerical results of the study show that the characteristics of nanofluid heat transfer increases with increasing volume fraction of nanoparticles. With increasing volume fraction, random motion and irregular particles increases energy exchange rate in the fluid and as a result increases the thermal dispersion of nanofluid. Moreover, the nanofluid velocity in the cavity center for higher Grashof is much smaller compared to the near-wall velocity. With increasing volume fraction, nanofluid velocity components increase as a result of the energy transfer within the fluid. The maximum vertical velocity component in this figure is for higher volume fraction.

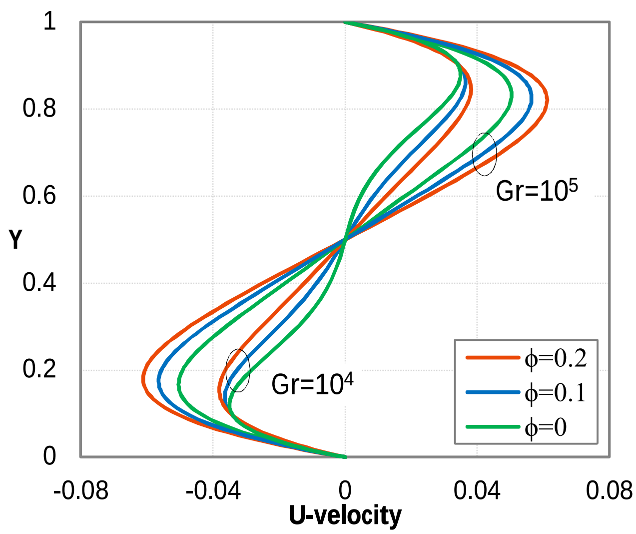

Figure (9)- Comparison of the U-velocity profiles between nanofluid and pure fluid for various Grashof numbers

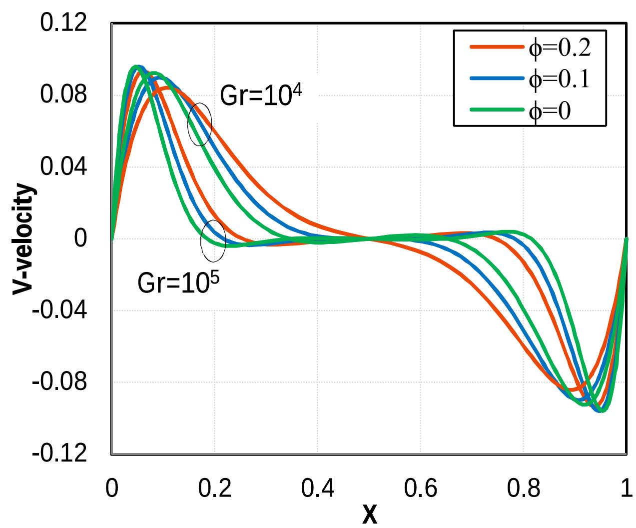

Figure (10)- Comparison of the V-velocity profiles between nanofluid and pure fluid for various Grashof numbers

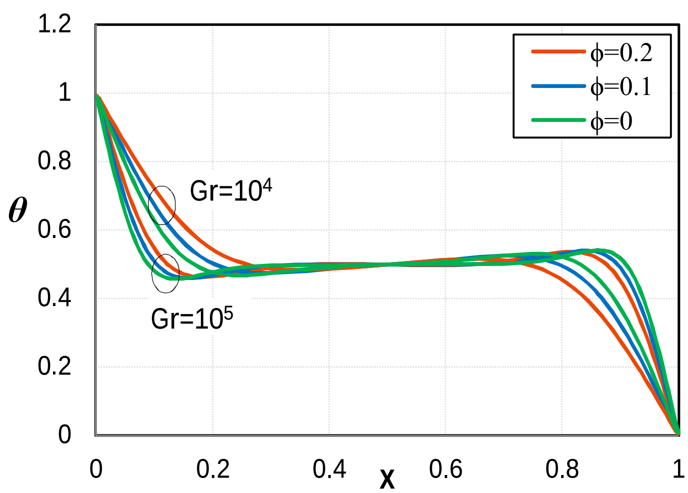

Figure (11)- Comparison of the temprature etprofiles bween nanofluid and pure fluid for various Grashof numbers

In figure (12), the effects of volume fraction on the local Nusselt number on the hot wall for Grashof number 10^5 and water-Cu nanofluid have been investigated. As can be seen, in higher volume fraction, the Nusselt number along the wall is much higher. The maximum Nusselt number at the bottom of the wall is higher than upper parts due to extreme changes in temperature.

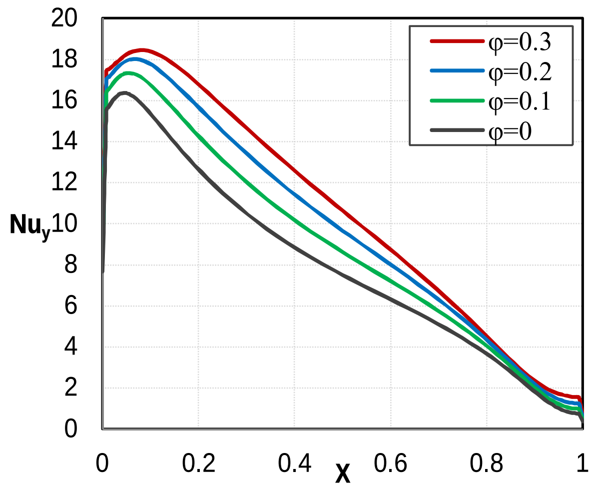

Figure (12)- Variation of local Nusselt number along the hot wall for Cu -water nanofluid at $Gr=10^5$.

In Figure (13), local Nusselt number on the hot wall for various nanofluids at Grashof number 10^5 and the volume fraction 0.2 is shown. As expected, the maximum Nusselt number along the wall is for water-Cu nanofluid and the least is for pure water.

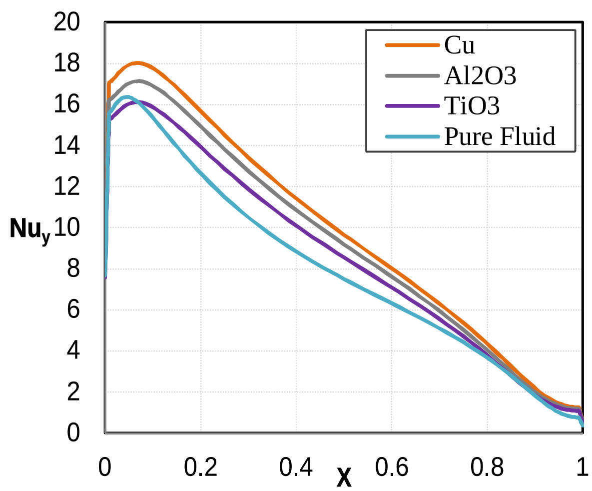

Figure (13)- Variation of local Nusselt number along the hot wall for different nano-particles at $Gr=10^5$ and $\varphi = 0.2$.

5.Conclusion

In this study natural convection heat transfer of nanofluids is studied using numerical method. The mechanism of thermal dispersion as a result of nanoparticles random motion is also considered as a factor in increasing heat transfer. Due to dependence of thermal dispersion on fluid velocity, the higher the Grashof number, the higher nanofluid vortex in the cavity which affects the increase in heat transfer.

In the presence of nanoparticles in the fluid, the fluid conductivity coefficient increases. This increase is different due to types of nanoparticles. The results of this study show that the highest increase in heat transfer based on the average Nusselt number for all Grashf numbers belongs to water-Cu nanofluid. This can be due to higher thermal conductivity of copper relative to that of other nanoparticles. According to experimental results, increased volume fraction raise thermal conductivity resulting in increased nanofluid heat transfer. Most of the effect nanoparticles is in the fluid transport properties, especially in the heat transfer properties,So nanofluids in heat exchanger, which can lead to significant reductions in fluid flow can be used in Oil & Gas refineries. Finally, the heat exchangers are designed with less weight and size. Also, due to the kinetic energy of particles hitting the surface, creating little Create friction and low wear And less damage to channels and pumps.

Nomenclature

C_p specific heat at constant pressure
d_p nanoparticle diameter
Gr Grashof number
H enclosure height
k thermal conductivity
L enclosure width
Nu average Nusselt number
Nu_x local Nusselt number
p pressure
Pr Prandtl number
T temperature
u,v velocity components
U,V Dimensionless velocity components
x,y Cartesian coordinates
X,Y dimensionless coordinates

Greek symbols

α thermal diffusivity
β thermal expansion coefficient
θ dimensionless temperature
μ dynamic viscosity
ν kinematic viscosity
ρ density
φ particle volume fraction

REFERENCES

[1] Masuda, H., Ebata, A., Teramae, K., and Hishinuma, N., 1993, "Alteration of Thermal Conductivity and Viscosity of Liquid by Dispersing Ultra-Fine Particles (Dispersion of γ-Al2O3, SiO2, and TiO2 Ultra-Fine Particles)," Netsu Bussei, 4(4), pp. 227-233.

[2] Choi, S. U. S., 1995, "Enhancing Thermal Conductivity of Fluids with Nanoparticles," Developments and Applications of Non-Newtonian Flows, D. A. Siginer, and H. P. Wang, eds., The American Society of Mechanical Engineers, New York, FED-Vol. 231 / MD-Vol.

[3] N. Putra, W. Roetzel, S.K. Das, Natural convection of nano-fluids,Heat Mass Transfer 39 (2003) 775–784.

[4] K. Khanafer, K. Vafai, M. Lightstone, Buoyancy-driven heat transfer enhancement in a two-dimensional enclosure utilizing nanofluids, Int. J. Heat Mass Transfer 46 (2003) 3639–3653.

[5] J. Kim, Y.T. Kang, C.K. Choi, Analysis of convective instability and heat transfer characteristics of nanofluids, Phys. Fluids 16 (2004) 2395–2401.

[6] Jou, R.Y., Tzeng, S.C., 2006. Numerical research of nature convective heat transfer enhancement filled with nanofluids in rectangular enclosures. Int. Comm. Heat Mass Transfer 33, 727–736.

[7] A. G. A. Nnanna, Experimental Model of Temperature-Driven Nanofluid, J. Heat Transfer , vol. 129, no. 6, pp. 697–704, 2007.

[8] Ghasemi B. and S.M. Aminossadati, (2009), Natural convection heat transfer in an inclined enclosure filled with a water-Cuo nanofluid, Numerical Heat Transfer, Part A, Vol. 55 pp. 807-823.

[9] M. A. Mansour , R. A. Mohamed , Sameh E. Ahmed,2011,"Natural convection cooling of a heat source embedded on the bottom of an enclosure filled with Cu-water nanofluid: effects of various thermal boundary conditions," Heat Mass Transfer, 47:1479–1490.

[10] Pak, B. C., and Cho, Y. I., 1998, "Hydrodynamic and Heat Transfer Study of Dispersed Fluids with Submicron Metallic Oxide Particles," Exp. Heat Transfer, 11(2), pp. 151-170.

[11] Chen, H., Ding, Y., and Lapkin, A., 2009, "Rheological Behaviour of Nanofluids Containing Tube / Rod-Like Nanoparticles," Powder Technol., 194(1-2), pp. 132-141.

[13] Maxwell, J. C., 1873, A Treatise on Electricity and Magnetism, Clarendon Press, Oxford.

[14] R.J. Krane, J. Jessee, Some detailed field measurements for a natural convection flow in a vertical square enclosure, Proceedings of the First ASME-JSME Thermal Engineer-ing Joint Conference, vol. 1, 1983, pp. 323–329.