INFLUENCE OF DIAMOND/OIL NANOFLUID ON NATURAL CONVECTION IN HEATED CYLINDRICAL ENCLOSURE

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Abstract

The objective of the present paper is to investigate diamond/oil nanofluid natural convection in partially heated cylindrical enclosure numerically. For this purpose numerical simulation if natural convection in partially heated cylindrical is carried out with pure oil and diamond/oil nanofluid. Calculation is performed based on the finite volume technique for three different Grashof numbers ($10^4 \le Gr \le 10^5$*) and the volume fraction of 0.04 (*$\Phi = 0.04$*). Results show that adding Nano diamond to pure oil not only changes the temperature field, but also alters the flow field significantly. It is demonstrated that by adding Nano diamond to the pure oil, thermal diffusion enhances to great extend which leads to the uniform radial distribution of temperature throughout the nanofluid in comparison to the pure oil. Moreover, thermal diffusion augmentation leads to the intensification of natural heat transfer and increasing of Nusselt number. It is also concluded that Nano diamond increases the viscosity of the nanofluid that results in the reduction of the vertical velocity especially at lower Grashof numbers.*

Key words: diamond/oil nanofluid; natural convection heat transfer; numerical simulation; Grashof numbers.

Nomenclature

C_p	specific heat at constant pressure
g	gravitational acceleration
h	local heat transfer coefficient
k	thermal conductivity
$Nu = \dfrac{hD}{k_f}$	Nusselt number
Nu_{ave}	average Nusselt number
Pr	Prandtl number
$Ra_D = \dfrac{g\beta}{\nu\alpha}(T_s - T_\infty)D^3$	Rayleigh number
$Gr = \dfrac{g\beta(T_S - T_\infty)D^3}{\nu^2}$	Grashof number
T	Temperature
u, v	dimensional x and v components of velocity
Greek symbols	
α	fluid thermal diffusivity
β	thermal expansion coefficient
φ	nanoparticle volume fraction
υ	kinematic viscosity
$\theta = \dfrac{T - T_\infty}{T_H - T_\infty}$	dimensionless temperature
ρ	density
μ	dynamic viscosity
Subscript	
nf	Nanofluid
eff	effective
f	fluid
s	soild
p	particle

1. Introduction

Heat transfer augmentation is an important issue in in engineering systems due to its wide applications in electronic cooling, heat exchangers, double pane windows etc. Enhancement of heat transfer in these systems is an essential topic from an energy saving perspective. The low thermal conductivity of convectional heat transfer fluids such as water and oils is a primary limitation in enhancing the performance and the compactness of such systems. An innovative technique to improve heat transfer is by using nano-scale particles in the base fluid [1].

Nanotechnology has been widely used in industry since materials with sizes of nanometers possess unique physical and chemical properties. Nano-scale particle added fluids are called as nanofluid that is firstly utilized by Choi in 1995 [1]. Some numerical and experimental studies on nanofluids include thermal conductivity [2] convective heat transfer [3-4], boiling heat transfer and natural convection [5]. Detailed review studies are published by [6-7].

Studies on natural convection using nanofluids are very limited and they are related with differentially heated enclosures. Hwang et al. [8] investigated the buoyancy-driven heat transfer of water-based Al_2O_3 nanofluids in a rectangular cavity. They showed that the ratio of heat transfer coefficient of nanofluids to that of base fluid is decreased as the size of nanoparticles increases, or the average temperature of nanofluids is decreased. Khanafer et al. [9] investigated the heat transfer enhancement in a two-dimensional enclosure utilizing nanofluids for various pertinent parameters. They tested different models for nanofluid density, viscosity, and thermal expansion coefficients. It was found that the suspended nanoparticles substantially increase the heat transfer rate any given Grashof number.

Natural convection heat transfer in a partially heated enclosure is an important issue due to wide applications in buildings or cooling of flush mounted electronic heaters. Chu et al.[10]conducted an experimental and numerical study to analyze the effects of heater size, location, aspect ratio and boundary conditions on natural convection in a rectangular air filled enclosure. They indicated that heater size and location are important parameters on flow and temperature field and heat transfer. The problem of temperature and flow field in a partially heated enclosure for different conditions in air or water filled enclosure has been studied extensively in the last three decades.

The main aim of this study is to examine the natural convection heat transfer in a partially heated cylindrical enclosure filled with diamond/oil nanofluid. Three different Grashof number are examined to investigate the effect of nanoparticles on natural convection flow and temperature fields. The mentioned literature survey indicates that there is no study on natural convection in a partially heated enclosure filled with diamond/oil nanofluid which considered as Non-Newtonian Nanofluid.

2. Problem Statement

The two dimensional validation test case for the present study is chosen according to the [9] They have investigated heat transfer and fluid flow due to buoyancy forces in a partially heated enclosure using nanofluids using different types of nanoparticles. The flush mounted heater is located to the left vertical wall with a finite length. The temperature of the right vertical wall is lower than that of heater while other walls are insulated. The finite volume technique is used to solve the governing equations. Calculations have been performed for Rayleigh number $10^3 \le Ra \le 5\times10^5$ (see Figure 1).

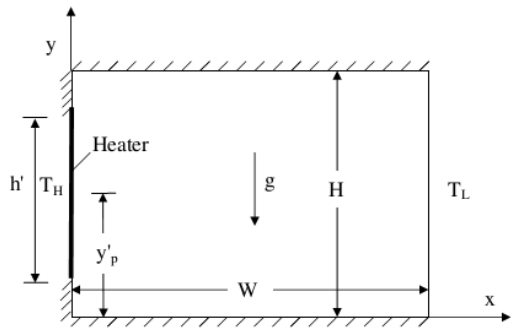


Figure 1: Sketch of problem geometry and coordinates for validation[9]

After the validation procedure, heat transfer and fluid flow because of natural convection in a partially heated cylindrical enclosure is performed. The computational domain is depicted in Figure 2. Figure 2 also presents the extent of the computational domain as X/D ×Y/D×Z/D in the x, y and z directions, respectively and D=1cm. The flow domain extends y/D vertically from the heated surface. The boundary conditions are as follow.

1. Heated part of the bottom wall (red color in the Figure 2) with constant value, dimensionless temperature of θ=1, θ=5 and θ=10 and no slip boundary condition.
2. Remaining part of the bottom wall is adiabatic of and no slip boundary condition.
3. Side walls are consisting of two parts. The first part related to the four extended surfaces wall as depicted in the Figure 2, which are modeled by convection boundary condition and conjugate heat transfer. On the remaining part of the cylinder enclosure the convection boundary condition is imposed.

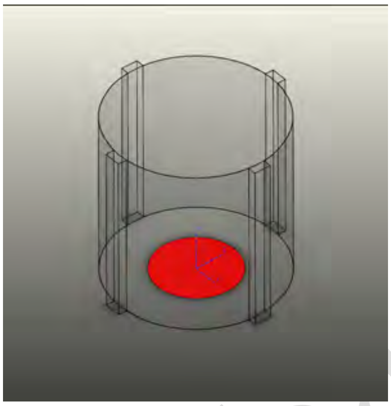


Figure 2: Sketch of problem geometry and coordinates for 3D simulation in cylindrical enclosure

3. Mathematical Formulation

3.1. Governing equations

The fluid in the cylindrical enclosure is a oil based nanofluid containing diamond type of nanoparticles. The nanofluid is assumed incompressible and the flow is assumed tobe laminar. It is assumed that the base fluid (i.e. Oil) and the nanoparticles are in thermal equilibrium and no slip occurs between them. The thermophysical properties of the nanofluid are given in Table 1.

Table 1: Thermophysical properties of fluid and nanoparticles

Thermophysical properties	Definition	Fluid Phase(Oil)	Nanoparticles (Diamonds)
$C_p(J/Kg°C)$	specific heat at constant pressure	1870	0.502
$\rho(kg/m^3)$	density	879	3500
$K(W/m°C)$	thermal conductivity	0.1318	1800
$\alpha(m^2/s)$	Thermal diffusivity	$27*10^{-6}$	10^{-3}
$\beta(1/°C)$	Thermal expansion coefficient	$7.15*10^{-4}$	1×10^{-6}

The governing equations for the laminar and steady state natural convection based on the Navier stocks formulation are:

$$\frac{\partial}{\partial x}[V_x\phi]+\frac{\partial}{\partial y}[V_y\phi]+\frac{\partial}{\partial z}[V_z\phi]=S \tag{1}$$

Where ϕ and S are defined as below for continuity, momentum and energy equations.

Governing equation	ϕ	S	
Continuity	1	0	(2)
x-momentum equation	V_x	$\frac{1}{\rho_{eff}}\left(\begin{array}{l} -\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}[2\mu\frac{\partial V_x}{\partial x}-\frac{2}{3}\mu(\frac{\partial V_x}{\partial x}+\frac{\partial V_y}{\partial y}+\frac{\partial V_z}{\partial z})]+ \\ \frac{\partial}{\partial y}[\mu(\frac{\partial V_x}{\partial y}+\frac{\partial V_y}{\partial x})]+\frac{\partial}{\partial z}[\mu(\frac{\partial V_x}{\partial z}+\frac{\partial V_z}{\partial x})] \end{array}\right)$	(3)
y-momentum equation	V_y	$\frac{1}{\rho_{eff}}\left(\begin{array}{l} -\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}[\mu(\frac{\partial V_x}{\partial y}+\frac{\partial V_y}{\partial x})]+\frac{\partial}{\partial y}[2\mu\frac{\partial V_y}{\partial y}-\frac{2}{3}\mu(\frac{\partial V_x}{\partial x}+\frac{\partial V_y}{\partial y}+\frac{\partial V_z}{\partial z})] \\ +\frac{\partial}{\partial z}[\mu(\frac{\partial V_y}{\partial z}+\frac{\partial V_z}{\partial y})]+g\rho_{eff}\beta_{eff}(T_H-T)] \end{array}\right)$	(4)
z-momentum equation	V_z	$\frac{1}{\rho_{eff}}\left(\begin{array}{l} -\frac{\partial p}{\partial z}+\frac{\partial}{\partial x}[\mu(\frac{\partial V_x}{\partial z}+\frac{\partial V_z}{\partial x})]+\frac{\partial}{\partial y}[\mu(\frac{\partial V_y}{\partial z}+\frac{\partial V_z}{\partial y})] \\ \frac{\partial}{\partial z}[2\mu\frac{\partial V_z}{\partial z}-\frac{2}{3}\mu(\frac{\partial V_x}{\partial x}+\frac{\partial V_y}{\partial y}+\frac{\partial V_z}{\partial z})] \end{array}\right)$	(5)
Energy equation	T	$\frac{k_{eff}}{\rho_{eff}C_{P_{eff}}}(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2})$	(6)

3.2. Nanofluid Properties Specification

The effective thermal conductivity of the nanofluid is calculated based on the Maxwell-Garnetts [] formulation as

$$\frac{k_{nf}}{k_f}=\frac{k_s+2k_f-2\phi(k_f-k_s)}{k_s+2k_f+\phi(k_f-k_s)} \quad (7)$$

The viscosity of the nanofluid can be approximated as viscosity of a base fluid containing dilute suspension of fine spherical particles and is given by Brinkman []

$$\frac{\mu_{nf}}{\mu_f}=\frac{1}{(1-\phi)^{2.5}} \quad (8)$$

The effective density, heat capacitance and thermal expansion of the nanofluid are given by

$$\begin{cases} \rho_{nf}=(1-\varphi)\rho_f+\varphi\rho_s \\ (\rho c_p)_{nf}=(1-\varphi)(\rho c_p)_f+\varphi(\rho c_p)_s \\ (\rho\beta)_{nf}=(1-\varphi)(\rho\beta)_f+\varphi(\rho\beta)_s \end{cases} \quad (9)$$

3.2. Numerical Details

For the simulation presented here, all the transport equations (momentum, energy) are discretized using a second-order upwind scheme. Pressure interpolation is second order. The SIMPLE algorithm is used for pressure velocity coupling. Convergence is assumed to be obtained when the scaled residuals reach 10^{-5}.

4. Grid resolution and validation

An extensive mesh testing procedure was conducted to guarantee a grid independent solution. The present code was tested for grid independence by calculating the average Nusselt number on the bottom wall. It is found that the present grid size ensures a grid independent solution. In Figure 3 the grid resolution on two plane of computational domain has been depicted.

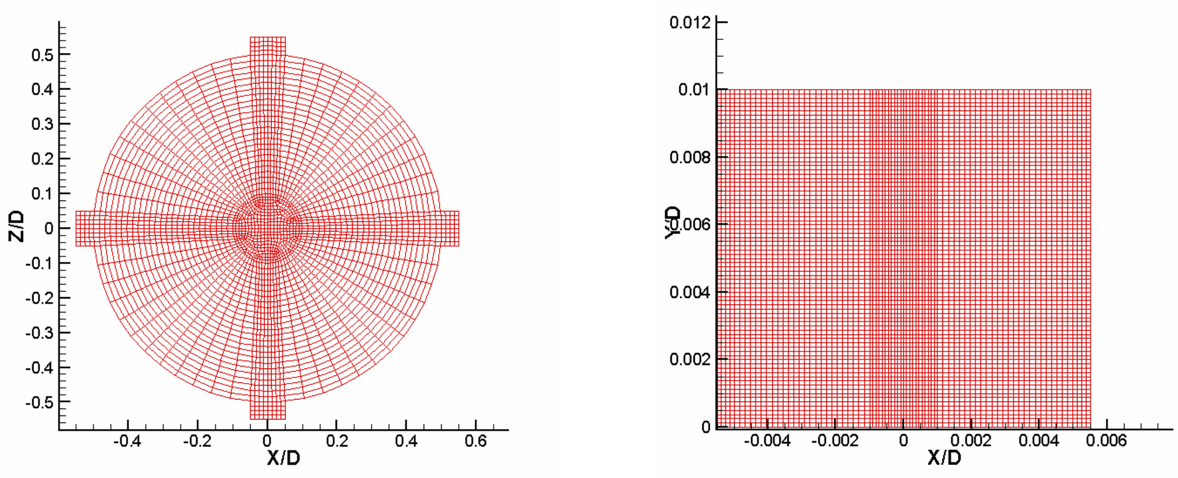


Figure 3: Close-up of resolution at **Left**) x-z plane and **Right**) x-y plane

The present numerical solution is further validated by comparing the present code results against the numerical simulation of Khanafer et al. (2003). It is clear that the present code is in good agreement with other work reported in literature as shown in Figure 4.

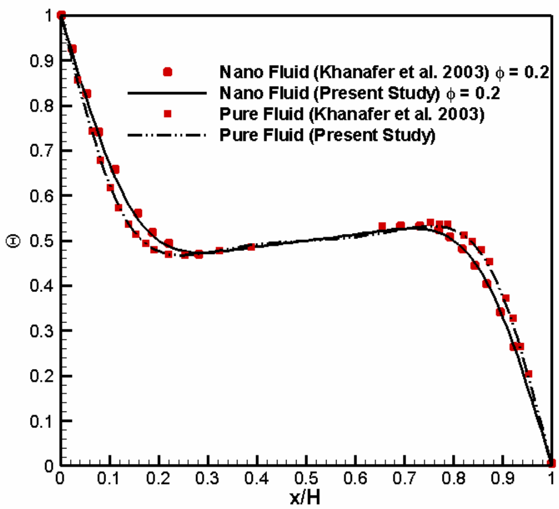


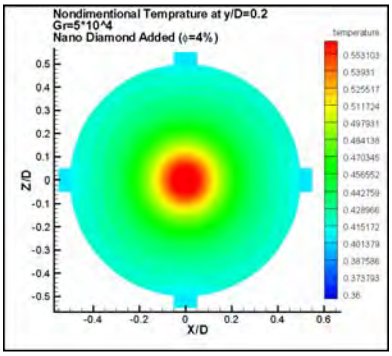
Figure 4: Comparison between present work and other published data for the temperature distribution

5. Results and Discussion

Numerical analysis of buoyancy induced flow in a partially heated enclosure filled with nanofluid has been performed using the laminar model. The effect of adding diamond nanoparticles with constant volume fraction of 0.04 and three different Grashof number are analyzed.

In Figure 5 the temperature distribution between pure oil and diamond/oil nanofluid at four elevation according to the bottom heat surface are present for $Gr = 5 \times 10^4$ and volume fraction of 0.04. It is clear that there is a distinct boundary between hot and cold flow in pure oil while it is completely different for nanofluid; the temperature field are fully uniform in nanofluid and the heat distribution is more uniform than pure oil. As it can be seen by adding Nano diamond to the pure oil, thermal diffusion enhances to great extend which leads to the uniform radial distribution of temperature throughout the nanofluid in comparison to the pure oil.

a)



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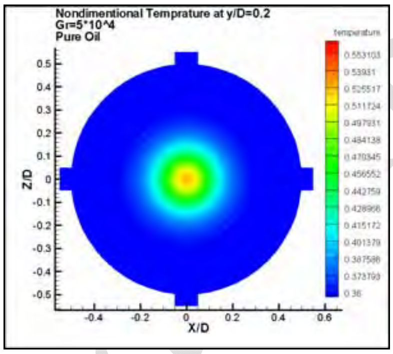

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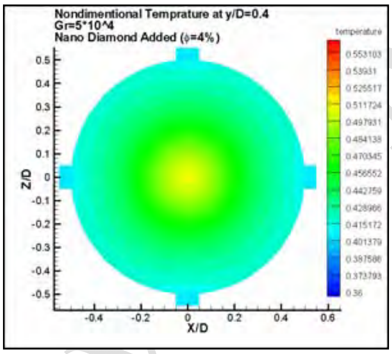

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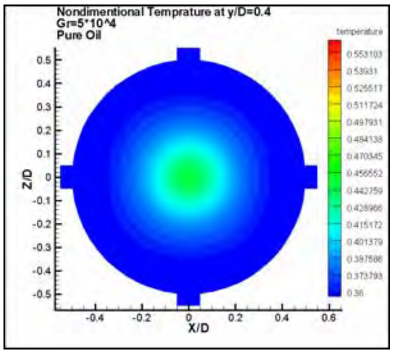

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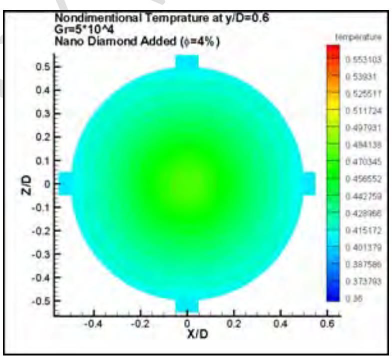

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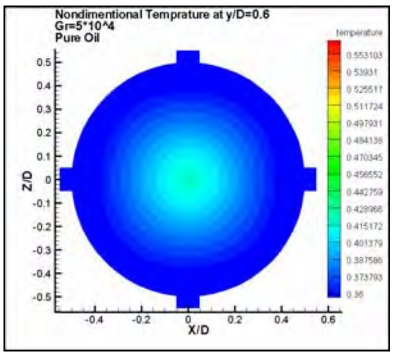

g)

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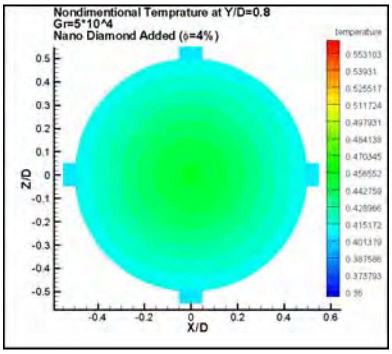


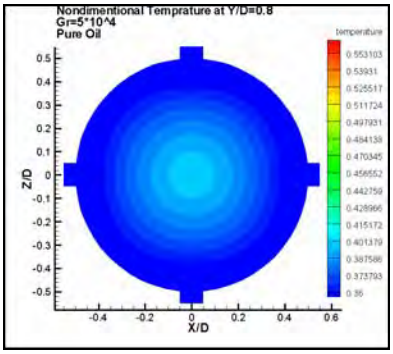
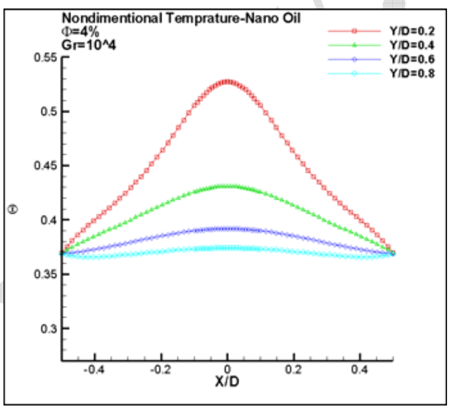


Figure 5: dimensionless temperature distribution (θ) comparison between pure oil and diamond/oil nanofluid at four elevation
a) Nanofluid at y/D=0.2, **b)** Pure oil at y/D=0.2, **c)** Nanofluid at y/D=0.4, **d)** Pure oil at y/D=0.4, **e)** Nanofluid at y/D=0.6, **f)** Pure oil at y/D=0.6, **g)** Nanofluid at y/D=0.8, **h)** Pure oil at y/D=0.2,

In Figure 6 the temperature profiles at four heights of y/D=0.2, y/D=0.4, y/D=0.6 and y/D=0.8 on centerline of z/D=0 plane for three Grashof numbers ($10^4 \le Gr \le 10^5$) are depicted. The constant volume fraction of 0.04 is chosen for nanofluid. As it can be seen in Figure 6, temperature gradient profiles toward the outer edge within the nanofluid is more smoother than pure oil, which confirms that by adding Nano diamond particles to the pure oil the thermal diffusion enhances significantly. In addition, the comparison of temperature profiles at the same heights demonstrate that addition of Nano diamond particles to pure oil increases the natural convection and improves the buoyancy mechanism, since the overall temperature magnitude is higher for the nanofluid in comparison to the pure oil at the same height. Furthermore, it is distinctive that by increasing the Grashof number the core of hot fluid is mostly concentered in the central region and the temperature gradient profile become very sharp. Although this trend is similar for both pure and nanofluid, the temperature gradient profile is smother for the diamond/oil nanofluid in comparison to the pure fluid.

a)



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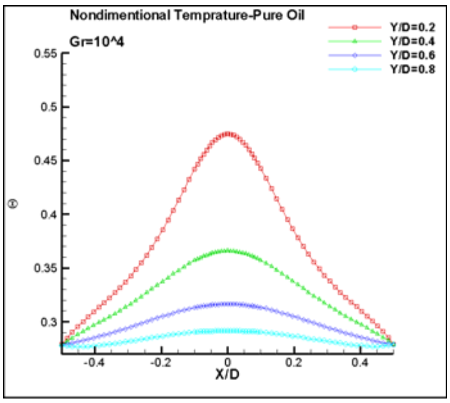

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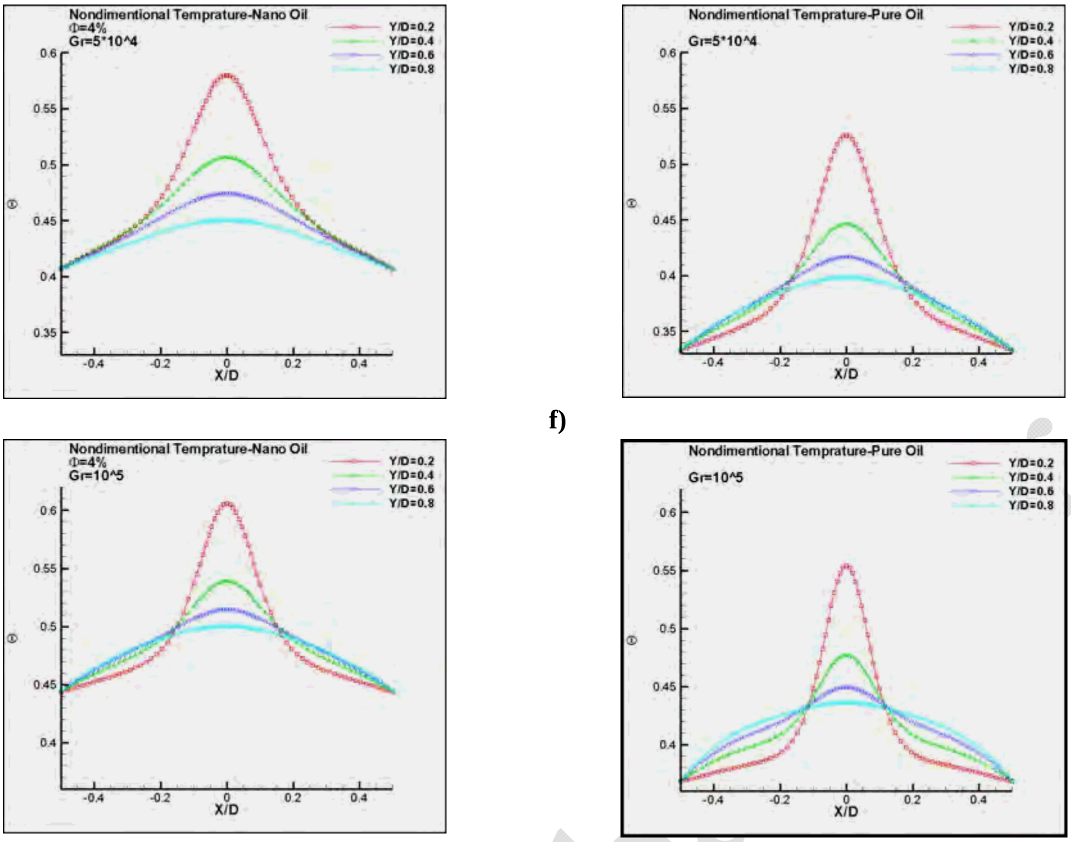
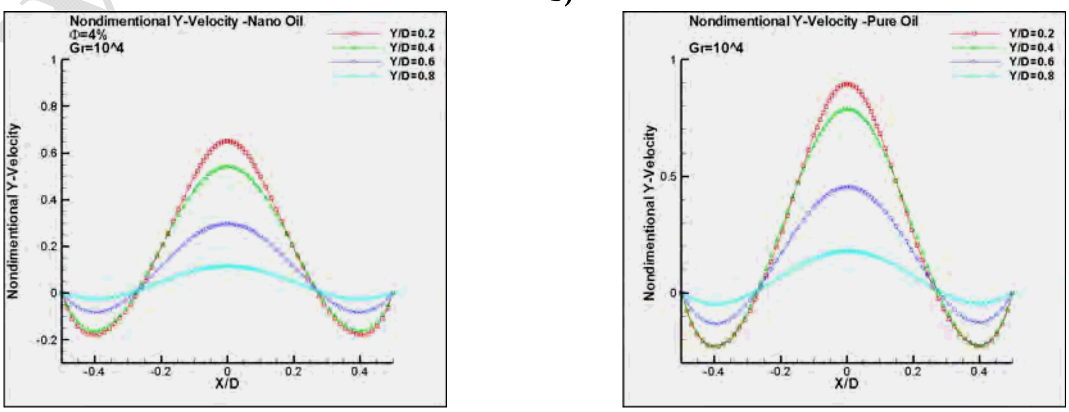


e) f)

Figure 6: temperature distribution comparison between pure oil and diamond/oil nanofluid at four elevations **a)** Nanofluid and $Gr = 10^4$, **b)** Pure oil and $Gr = 10^4$, **c)** Nanofluid and $Gr = 5\times10^4$, **d)** Pure oil and $Gr = 5\times10^4$, **e)** Nanofluid and $Gr = 10^5$, **f)** Pure oil and $Gr = 10^5$

Figure 7 shows the effects of Nano diamond particles on vertical velocity distribution for three Grashof number. Results show that adding Nano diamond to pure oil not only changes the temperature field (Figure 6), but also alters the flow field significantly. It is apparent that that Nano diamond increases the viscosity of the nanofluid and reduces the vertical velocity especially at lower Grashof numbers. It is interesting to note that although the vertical velocity is reduce in nanofluid in comparison to the pure fuild, the natural convection increases and the Nusselt number enhances (see Figure 8) .The reason is that addition of Nano diamond particles to the pure oil improve the thermal condition significantly which result to the thermal diffusivity augmentation.

a) b)



c) d)

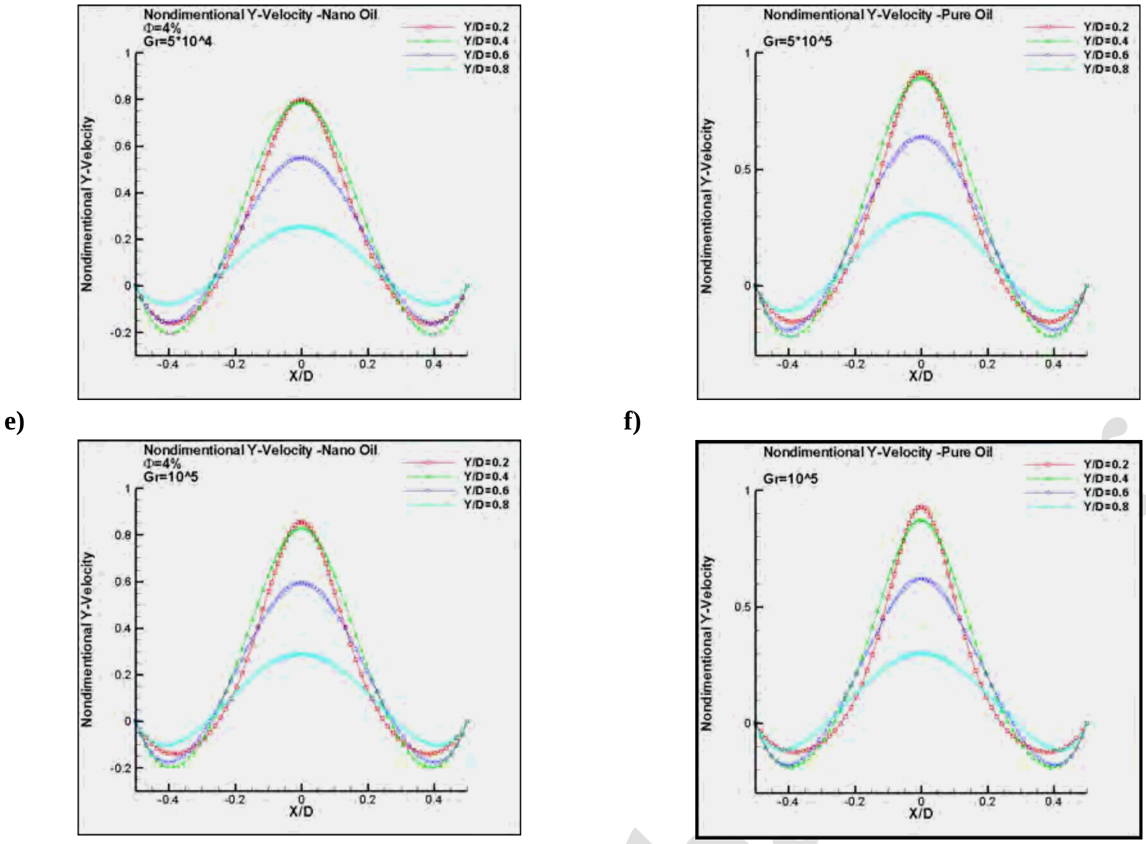


Figure 7: dimensionless vertical distribution comparison between pure oil and diamond/oil nanofluid at four elevations

a) Nanofluid and $Gr = 10^4$, **b)** Pure oil and $Gr = 10^4$, **c)** Nanofluid and $Gr = 5\times10^4$, **d)** Pure oil and $Gr = 5\times10^4$, **e)** Nanofluid and $Gr = 10^5$, **f)** Pure oil and $Gr = 10^5$

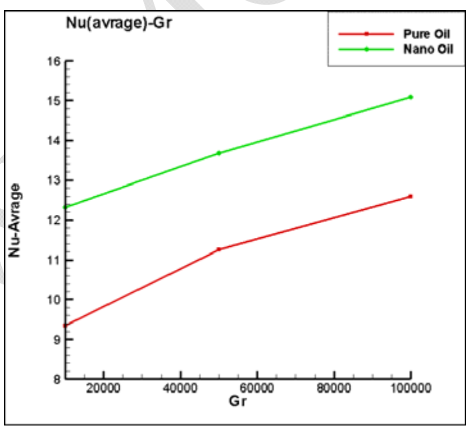


Figure 8: Effect of adding Nano diamond particles on mean Nusselt number for three different Grashof number

6. Conclusion

A numerical study has been performed to investigate the effect of using different nanofluid on natural convection flow field and temperature distributions in partially heated enclosure. Some important points can be drawn from the obtained results. Results show that addition of Nano diamond particles to the pure oil can enhance the natural convection significantly. It is demonstrated that thermal diffusivity of the nanofluid increase favorably and improves the thermal diffusion throughout the nanofluid. In addition it is concluded that adding diamond Nano particles to the pure oil increase the viscosity and reduce the vertical velocity which reduce the buoyant force, but it cannot deteriorate the positive influence of the improve thermal diffusivity.

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