TiO_2 Nanofluid in an Enclosure of Composite Material with Various Based Fluids

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Abstract: ***This paper presents a numerical study of steady state natural convection heat transfer of TiO_2 nanofluid in a horizontal annulus between two coaxial cylinders. The annulus material is made of Graphite/epoxy laminated composite materials. The Four different nanoparticles volume fractions are taken with the range of $(0 \leq \varphi \leq 0.4)$, modified Rayleigh number $(10 \leq R_a^* \leq 1000)$ and abased fluid of water and Ethylene Glycol (EG) with percents of $(0 \leq EG \leq 90)$. The Finite difference approximation is used to solve the governing equations. The results show that at $Ra^*=10$, adding nanoparticles to the pure water of 0% Ethylene glycol (EG) cause an enhancement in heat transfer of 344.7% for $\varphi= 0.4$ TiO_2. A base fluid of 30% EG in water at $R^{a*}=1000$ and with $\varphi=0.4$ enhance the heat transfer with 392.6% and 430% enhancement in heat transfer will be obtained for 90% EG in water with $Ra^*=1000$ and $\varphi=0.4$. A correlation for Nu related with Ra, φ and % EG, has been developed for inner cold cylinder.***

Keywords: Natural convection, laminar flow, porous media, TiO_2 nanofluid, Ethylene Glycol, composite material.

1. Introduction

Nanofluids have many applications in heat transfer field and are considered to have great potential for heat transfer enhancement. Recently, numerous studies are done in this field to investigate and explain the cause of the enhancement in heat transfer when the nanofluid is used as the working fluid. The researches include various geometry configurations as in [1] , [2] and [3] or concern with the changing of the types of nanoparticles used, based fluids, fluid flow, the nanoparticles volume fraction etc. as in [4], [5] and [6].

[1] Carried out experiments to study the heat transfer and fluid flow due to buoyancy forces in a partially heated enclosure using nanofluids using different types of nanoparticles. The finite volume technique is used to solve the governing equations. Different types of nanoparticles were tested. An increase in mean Nusselt number was found with the volume fraction of nanoparticles for the whole range of Rayleigh number.

[2] Investigated numerically the natural convection fluid flow and heat transfer inside C-shaped enclosures filled with Cu-Water nanofluid using finite volume method and SIMPLER algorithm. It was found that the mean Nusselt number increased with increase in Rayleigh number and volume fraction of Cu nanoparticles regardless aspect ratio of the enclosure. Moreover the rate of heat transfer increased with decreasing the aspect ratio of the cavity.

[3] Studied numerically the heat transfer and flow field in a wavy channel with nano-fluid. The control volume approach based on the SIMPLE technique is used to solve the governing equations numerically. It is concluded that heat transfer in channels can enhance by addition of nano-particles, and usage of wavy horizontal walls by 50%.

[4] Investigated numerically the problem of mixed convection fluid flow and heat transfer of Al2O3-water nanofluid with temperature and nanoparticles concentration dependent thermal conductivity and effective viscosity inside a square cavity. It is found that when the heat source was located in the middle of bottom wall and the Rayleigh number was kept constant, the effect of addition of nanoparticles on enhancement of heat transfer increased with increase in Reynolds number.

[5] Studied experimentally the heat transfer coefficient and friction factor for flow in a tube and with twisted tape inserts in the transition range of flow with Al2O3 nanofluid. The results showed considerable enhancement of convective heat transfer with Al2O3 nanofluids. The maximum friction factor with twisted tape at 0.1% nanofluid volume concentration is 1.21 times that of water flowing in a plain tube.

[6] A differentially heated enclosure filled with a CuO-EG-Water nanofluid was investigated to study the natural convection heat transfer characteristics for different published variable thermal conductivity and variable viscosity models. The resulting governing equations are solved numerically using an efficient finite-volume method.

Different behaviors (enhancement or deterioration) are predicted in the average Nusselt number as the volume fraction of nanoparticles increases depending on the combination of CuO-EG--Water variable thermal conductivity and viscosity models. The enclosure aspect ratio is predicted to have significant effects on the behavior of the average Nusselt number which decreases as the enclosure aspect ratio increases.

2. Objective of Research

This research investigates numerically the steady state natural convection heat transfer of TiO_2 nanofluid in a horizontal annulus between two coaxial cylinders. Eight annular fins are attached to the inner cylinder and the annulus filled with silica sand. Graphite/epoxy composite material has a maximum thermal conductivity of 11.1 W/m K when the direction of fibers is in parallel [7] which is taken into consideration in the present research. The parameters affected are the volume fractions $(0 \le \varphi \le 0.4)$, modified Rayleigh number $(10 \le R_a^* \le 1000)$ and abased fluid of water and Ethylene Glycol with percents of $(0 \le EG \le 90)$.

3. Mathematical Model

Fig. 1 illustrates the geometry and the Cartesian coordinate system used in solving the problem**.** The model of incompressible flow in the porous medium (Darcy flow model), the mass, the momentum (Darcy), the energy conservation laws and the Boussinesq's approximation are employed and are given in vectorial notation by [8].

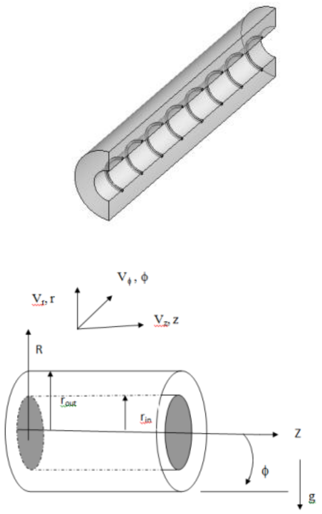


Figure 1: Geometry and coordinates system

The TiO_2 particles are assumed to be spherical, so the Maxwell-Garnetts model of effective thermal conductivity will be applied as in [9, 10]:

$$\frac{k_{nf}}{k_f} = \frac{k_s + 2k_f - 2\phi\,(k_f - k_s)}{k_s + 2k_f + \phi\,(k_f - k_s)} \quad (1)$$

The viscosity of the nano-fluid can be also taken for spherical particles and approximated as viscosity of a base fluid μ_f containing dilute suspension of fine particles and is given by [11]:

$$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}} \quad (2)$$

Now a transformation will be done to the governing equations which are continuity, momentum and energy equations to dimensionless equations, then the vector potential equations are obtained in the dimensionless form as [12]and [13]:

$$\frac{\partial U_r}{\partial R} + \frac{U_r}{R} + \frac{1}{R}\frac{\partial U_\phi}{\partial \phi} + \frac{\partial U_z}{\partial Z} = 0 \quad (3)$$

$$Ra^* \Pr * C_1 * \left(\sin\phi \frac{\partial \theta}{\partial Z}\right) = -\frac{\partial^2 \psi_r}{\partial R^2} - \frac{1}{R^2}\frac{\partial (R\psi_r)}{\partial R} - \frac{2}{R}\frac{\partial \psi_r}{\partial R} - \frac{1}{R^2}\frac{\partial^2 \psi_r}{\partial \phi^2} - \frac{\partial^2 \psi_r}{\partial Z^2} - \frac{2}{R}\frac{\partial \psi_z}{\partial Z} \quad (4)$$

$$Ra^* \Pr C_1 * \left(\cos\phi \frac{\partial \theta}{\partial Z}\right) = -\frac{\partial^2 \psi_\phi}{\partial Z^2} - \frac{\partial^2 \psi_\phi}{\partial R^2} - \frac{1}{R^2}\frac{\partial^2 \psi_\phi}{\partial \phi^2} - \frac{2}{R^2}\frac{\partial \psi_r}{\partial \phi} + \frac{\psi_\phi}{R^2} - \frac{1}{R}\frac{\partial \psi_\phi}{\partial R} \quad (5)$$

$$-\frac{Ra^* \Pr C_1}{\alpha_{nf}}\left(\frac{1}{R}\cos\phi \frac{\partial \theta}{\partial \phi} + \sin\phi \frac{\partial \theta}{\partial R}\right) = -\frac{\partial^2 \psi_z}{\partial R^2} - \frac{1}{R}\frac{\partial \psi_z}{\partial R} - \frac{1}{R^2}\frac{\partial^2 \psi_z}{\partial \phi^2} - \frac{\partial^2 \psi_z}{\partial Z^2} \quad (6)$$

Where $C_1 = \frac{\alpha_f}{\alpha_{nf}}\left[(1-\varphi) + \varphi\frac{(\rho\beta)_s}{(\rho\beta)_f}\right](1-\varphi)^{2.5}$

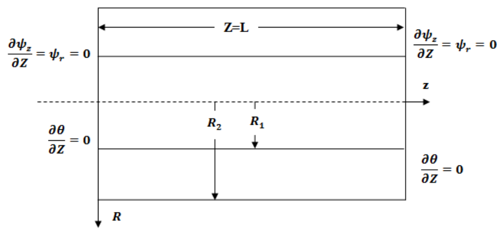
And the energy equation will be:

$$\left(\frac{1}{R}\frac{\partial \psi_z}{\partial \phi} - \frac{\partial \psi_\phi}{\partial Z}\right)\frac{\partial \theta}{\partial R} + \frac{1}{R}\left(\frac{\partial \psi_r}{\partial Z} - \frac{\partial \psi_z}{\partial R}\right)\frac{\partial \theta}{\partial \phi} + \left(\frac{\psi_\phi}{R} + \frac{\partial \psi_\phi}{\partial R} - \frac{1}{R}\frac{\partial \psi_r}{\partial \phi}\right)\frac{\partial \theta}{\partial Z} = \frac{\alpha_{nf}}{r_2}\left[\frac{\partial^2 \theta}{\partial R^2} + \frac{1}{R}\frac{\partial \theta}{\partial R} + \frac{1}{R^2}\frac{\partial^2 \theta}{\partial \phi^2} + \frac{\partial^2 \theta}{\partial Z^2}\right] \quad (7)$$

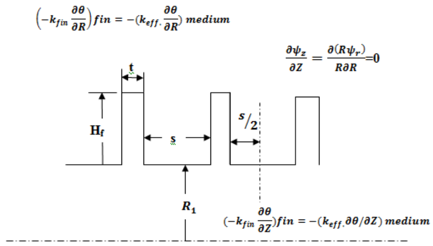
And fin equation will be [14]:

$$\frac{\partial \theta}{\partial R} + \frac{\theta}{R} + \frac{1}{R}\frac{\partial \theta}{\partial \phi} + \frac{\partial \theta}{\partial Z} = 0 \quad (8)$$

To obtain the final equations in the finite approximation form, equations (3, 4, 5, 7 and 8) are transformed applying the upwind differential method in the left hand side of the energy equation and the centered – space differential method for the other terms and solved by using (SOR) method as [15]. A mat lab computer program was built to meet the requirements of the problem. **Fig. 2**. illustrates the vector potential field with the boundary conditions.



Annulus boundary conditions



Fin Boundary conditions

Figure 2: Annulus and fins boundary conditions

4. Calculation of the Average Nusselt Number

The average Nusselt number Nu_{hot} and Nu_{cold} on the inner and the outer cylinders are defined as:

$$Nu_{hot} = -(1-R_1)\frac{k_{nf}}{k_f}\frac{1}{\pi L}\int_0^L\int_0^\pi\left(\frac{\partial\theta}{\partial R}\right)_{R=R} d\phi\, dZ \quad (9)$$

$$Nu_{cold} = -(1-R_1)\frac{k_{nf}}{k_f}\frac{1}{\pi L}\int_0^L\int_0^\pi\left(\frac{\partial\theta}{\partial R}\right)_{R=1} d\phi\, dZ \quad (10)$$

5. Results

Nu is an indication of heat transfer, so **Fig. 3** shows an increase in heat transfer as the modified Rayleigh number R^* increase. Adding nanoparticles to the pure water (0% EG) cause an enhancement in heat transfer and the enhancement will be 344.7% when adding particles with 0.4 TiO_2 volume fraction at Ra^*=10. A base fluid of water and 30% Ethylene glycol at Ra^*=1000 and with 0.4 TiO_2 volume fraction enhance the heat transfer 392.6% as in **Fig. 4**. An enhancement in heat transfer of 430% is obtained for a nanofluid of water and 90% EG Ra^*=1000 and with 0.4 TiO_2 volume fraction as shown in **Fig. 5.**

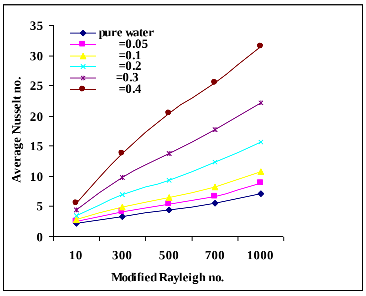


Figure 3: The variation of the average Nu with Ra^* for different TiO_2 volume fraction in 0% EG

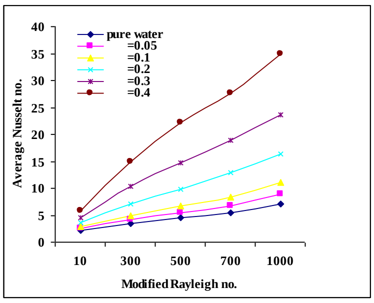


Figure 4: The variation of the average Nu with Ra^* for different TiO_2 volume fraction in based fluid of 30% EG

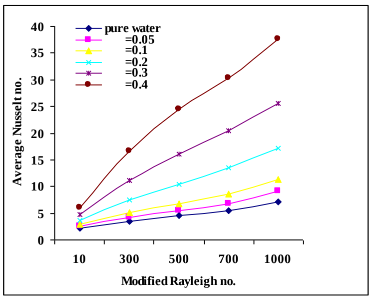


Figure 5: The variation of the average Nu with Ra^* for different TiO_2 volume fraction in based fluid of 90% EG

The variation of the average Nu with the percent of Ethylene glycol is illustrated in **Fig. 6** and **Fig. 7** for Ra^* equal 10 and 1000 respectively. These figures show the effect of both adding nanoparticles and changing the percent of Ethylene glycol in water on the enhancement of heat transfer.

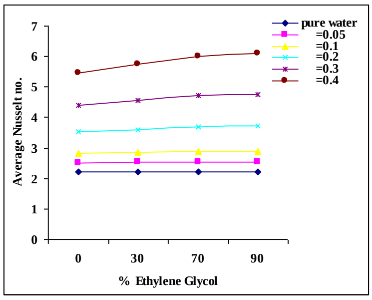


Figure 6: The variation of the average Nu with the % of EG in water for different TiO_2 volume fraction and Ra^*=1000

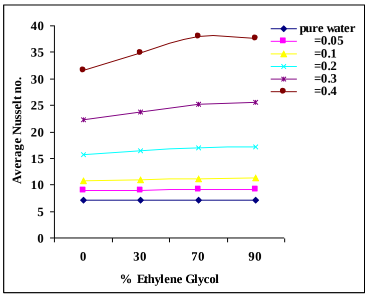


Figure 7: The variation of the average Nu with the % of EG in water for different TiO_2 volume fraction and Ra^*=10

Fig. 8 show the variation of the average Nu with TiO_2 volume fraction at Ra^*=1000 and for different percent of Ethylene glycol in water. It is clear that adding Ethylene glycol to water cause to enhance heat transfer significantly. Water/Ethylene glycol in the percent of 90% cause an enhancement in heat transfer of 430% for φ=0.4 and 344% enhancement for φ=0.4 and 0% EG.

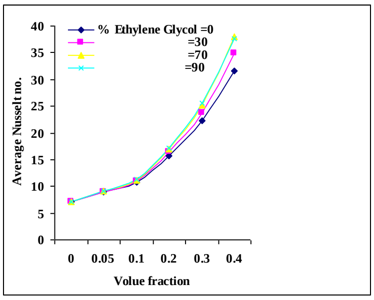


Figure 8: The variation of the average Nu with the TiO_2 volume fraction for Ra^* =1000 and different % of EG in water

Fig. 9 and **Fig. 10**show the distribution of the local Nu along the length of the cylinder and in the angular direction for %EG =90 with Ra^*=10 and 1000 respectively. The wavy of the curve is due to the existing of eight fins attached to the inner cylinder. The side of the red color is on the inner hot cylinder and it is clear that because the cylinder is horizontal, the local Nu is uniform along the length of the cylinder. The value of the local Nu increases in **Fig. 10,** so the region with the blue color becomes wider because of the enhancement in heat transfer. The same behavior will be noticed for Fig. 11 and Fig. 12 when TiO_2 nanoparticles are added with φ=0.4 and more enhancement in heat transfer will be obtained.

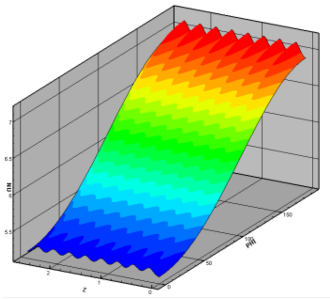


Figure 9: Local Nu along the cylinder length and in angular direction for Ra^*=10, φ=0 and % EG=90

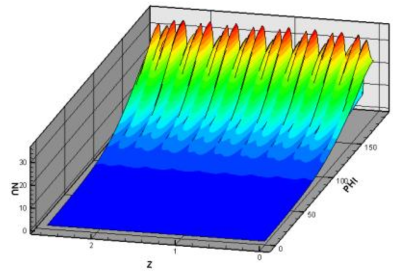


Figure 10: Local Nu along the cylinder length and in angular direction for Ra^*=1000, φ=0 and % EG=90

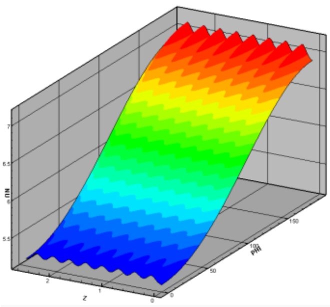


Figure 11: Local Nu along the cylinder length and in angular direction for Ra^*=10, φ=0.4 and % EG=90

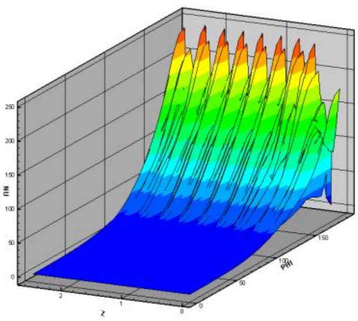


Figure 12: Local Nu along the cylinder length and in angular direction for Ra^*=1000, φ=0.4 and % EG=90

A correlation for Nu in terms of Ra, φ and % EG, has been developed for inner cold cylinder as follow:

$$Nu = 2.128\, R_a^{0.288}\, \varphi^{6.354}\, \%\, EG^{3.3}$$

6. Conclusions

The following major conclusions can be drawn from the study:

1) Adding nanoparticles to the pure water (0% EG) cause an enhancement in heat transfer of 344.7% for φ= 0.4 TiO_2 volume fraction at Ra^*=10.
2) A base fluid of water and 30% Ethylene glycol at R^{a*}=1000 and with φ=0.4 enhance the heat transfer 392.6%
3) 430% enhancement in heat transfer will be obtained when 90% EG in water will be used with Ra^*=1000 and φ=0.4.

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