Numerical Investigation of Turbulent Flow and Heat Transfer Characteristics of PGW-CuO Nanofluids

M.T.Naik[1], E.Vojkani[2]. and G.Ravi[3]

***Abstract*—** In this paper, turbulent convection flow of CuO nanofluids of propylene glycol-water (30:70 by volume) as the base fluid and flowing in a circular tube, subjected to a constant and uniform heat flux at the wall, is numerically analyzed. The effects of nanoparticles concentrations and Reynolds number are investigated on the flow and the convective heat transfer behavior of CuO nanofluids. It is found that nanofluids containing more concentrations have shown higher heat transfer coefficient. The analysis is carried out in the nanoparticles volume concentration range from 0.1% to 1.2%. The heat transfer coefficient increases by 9% for 1.2% CuO nanofluids over the base fluid. The numerical results are compared with the experimental data and reasonable good agreement is achieved.

***Keywords*—** Heat transfer coefficient, Nanofluids, Numerical analysis, Propylene glycol

I. INTRODUCTION

NANOFLUID is a liquid containing metallic particles of nanometer dimension; these fluids are engineered by colloidal suspensions of nanoparticles in a base fluid, which have a better suspension stability compared to millimetre or micrometer sized ones [1]. Nanofluids have novel properties that make them potentially useful in many applications. They exhibit enhanced thermal conductivity and the convective heat transfer coefficient compared to the base fluid [2].The theoretical models such as Maxwell and Hamilton-Crosser [4] are also available to predict the thermal conductivity of solid – liquid mixtures. Li and Xuan [5] investigated experimentally for 35nm copper nanofluid flowing in a circular tube under constant heat flux shows the enhancement of heat transfer coefficient from 1.05 to 1.14 times for the volume concentration in the range of 0.5-1.2% respectively, under the same flow of velocity. Xuan and Li [6] have been studied the CuO nanofluid up to 2% volume concentration and developed a new correlation with effect of volume concentration for Nusselt number. Maiga et al. [7, 8] developed a new correlation for the estimation of Nusselt number for Al_2O_3 nanofluids. Pak and Cho [9] observed the heat transfer enhancement with Al_2O_3 and TiO_2 nanofluid in circular tube and reported that Nusselt number increased by 30% over the Dittus-Boelter [10] equation for single-phase fluids.

Nanofluids containing nanoparticles exhibit highbred thermal conductivity. For example, a maximum increase in thermal conductivity of approximately 22% was observed in a CuO/EG nanofluid containing 4 vol. % CuO nanoparticles with the average diameter of 23.6 nm [11].

A similar behavior was observed in alumina/EG and Cu/EG nanofluids [12]. In other words, all the above experimental data are much larger than the theoretical predictions according to the existing models for the effective conductivity of a solid/liquid suspension.Propylene glycol and water (PG/water) based nanofluids are antifreezing liquids used for heat transfer application in cold regions,

A study by L. Syam Sundar, K.V. Sharma et al. [13] and Praveen K. Namburu et al. [14] presented the numerical study of hydrodynamic and thermal behaviors of fully developed turbulent flow of Al2O3/water, (CuO, Al2O3 and SiO2) in an ethylene glycol and water mixture nanofluids inside a circular tube subjected to a uniform heat flux and They observed that the heat transfer coefficient of nanofluid are slightly higher than the base fluid.

Comparisons of the computed Nusselt number with the correlations developed by Pak and Cho [9] and Maiga et al. [7, 8] have been presented. M.T.Naik, G.Rangajanardhana, (2010) studied thermal conductivity of CuO nanofluids up to 1.2% volume concentration and developed a new correlation with effect of volume concentration [15]. M.T.Naik, L.Syam Sundar, [16] studied the thermo- physical properties of PG-water CuO nanofluid, developed a new correlation with effect of temperature and concentration on thermal conductivity and viscosity. They showed that thermal conductivity increase with increase in temperature and viscosity decreases with increase in temperature of nanofluids.

II. THERMOPHYSICAL PROPERTIES OF NANOFLUIDS

Thermo physical properties of nanofluids are calculated by Pak and Cho [9]. Calculation of the thermal and physical properties of the nanofluids can be done as follows:

$$\mu_{nf} = \mu_{bf}\ (1 + 2.5\varphi + 6.2\ \varphi 2) \qquad (3)$$

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A. Thermal conductivity

According to the results of M.T.Nike et al.'s [16], the effective thermal conductivity is determined for PG-Water CuO nanofluid up to 1.2% concentration as follows:

$$K_{nf}/K_{bf} = 0.9533 \left(T_{max}/T_{min}\right)^{0.1824} (1+\varphi)^{0.2290} \quad (4)$$

The properties of base fluid, PG/water at different temperatures (>293 K) are available in ASHRAE [18]. These properties as a function of temperature were curve fitted from ASHRAE data. Then they were substituted in the density, specific heat, viscosity and thermal conductivity equations (1), (2), (3) and (4) to evaluate the properties of nanofluids at different temperatures and concentrations. Therefore, in our simulations the properties of nanofluids are temperature dependent. The properties of solid particles are taken to be constant in the present operating range of 293 K to about 343 K, the highest encountered temperature near the wall that occurs at a Reynolds number of 10^4.

III. Mathematical Modeling

A. Assumptions

The thermal and physical properties are temperature dependent under the operating conditions. The effective thermo physical properties are dependent upon the temperature and volume concentration. Furthermore the assumption for single phase for a nanofluid is validating to an experimental results of Pak and Cho [9]. Under these assumptions, the classical theory of single-phase fluid can be applied to nanofluid.

B. Governing equation

The problem under investigation is 2D steady, forced turbulent convection flow of nanofluid flowing inside a straight circular tube and subjected to a constant and uniform heat flux at the wall.

The governing equations for the fluid flow are [19]:

$$div\,(\rho\bar{V}) = 0 \quad (5)$$

$$div\,(\rho\bar{V}\bar{V}) = -grad\,(\bar{P}) + \mu\nabla^2\bar{V} - div\,(\rho u'u') \quad (6)$$

$$div\left(\rho\bar{V}C_pT\right) = div\,(k\ grad\,\bar{T} - \rho C_p u't') \quad (7)$$

In the above equations, the symbols $\bar{V}$, $\bar{P}$ and $\bar{T}$ represent the time averaged flow variables, while the symbols $\acute{u}$ and t' represent the fluctuations in velocity and temperature. The terms in the governing equations $\rho u'u'$ and $\rho c_p\, u't'$ represent the turbulent shear stress and turbulent heat flux. The terms are unknown and must be approximately expressed in terms of mean velocity and temperature.

C. Turbulent modeling

For closure of the governing equations of fluid flow, empirical data or approximate models are required to express the turbulent stresses and heat flux quantities of the related physical phenomenon. In the present numerical analysis, $k-\varepsilon$ turbulent model proposed by Launder and Spalding [20] was adopted. $k-\varepsilon$ turbulent model introduces two additional equations namely turbulent kinetic energy (k) and rate of dissipation (ε). The equations for turbulent kinetic energy (k) and rate of dissipation (ε) are given by:

$$div\,(\rho\bar{V}k) = div\left\{\frac{(\mu+\mu_t)}{\sigma_k\ grad\ k}\right\} + Gk - \rho\varepsilon \quad (8)$$

$$div\,(\rho\overline{V\varepsilon}) = div\left\{\frac{(\mu+\mu_t)}{\sigma_\varepsilon\ grad\ \varepsilon}\right\} + C_{1\varepsilon}\left(\frac{\varepsilon}{k}\right)G_k + C_{2\varepsilon}\rho\left(\frac{\varepsilon^2}{k}\right) \quad (9)$$

In the above equations, G_k represents the generation of turbulent kinetic energy due to mean velocity gradients, σ_k and σ_ε are effective Prandtl numbers for turbulent kinetic energy and rate of dissipation, respectively; $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are constants and μ_t is the eddy viscosity and is modeled as:

$$\mu_t = \frac{\rho C_\mu k^2}{\varepsilon} \quad (10)$$

C_μ is a constant and its value is 0.09.

In Eqs. (8) and (9); $C_{1\varepsilon}$ = 1.44; $C_{2\varepsilon}$ = 1.92; σ_κ = 1.0 and σ_ε = 1.3. Further information is available in Launder and Spalding [20] and Fluent [21] for turbulence modelling.

D. Boundary conditions

The geometrical configurations consist of a tube with length (L) of 1.5 (m) and circular section with the diameter (D) equal to 0.016 (m). The considered nanofluid is a mixture composed of PG-water (30:70 by volume) and particles of CuO, with a diameter of less than 50 nm. It is subjected to a constant and uniform heat flux at the wall, q$\acute{\circ}$ = 20000 (w/m2). At the tube inlet section, uniform axial velocity Vin temperature Tin=298 (k) turbulent intensity and hydraulic diameter have been specified. At the outlet section, the flow and temperature fields are assumed fully developed the flow and temperature fields are assumed fully developed (x/D > 10). The Reynolds number were varied from 10,000 to 50,000.

E. Numerical model

The computational fluid dynamics code Fluent was used for solving this problem. The system of governing equations (5)–(10) were solved by control volume approach. Control-volume technique converts the governing equations to a set of algebraic equations that can be solved numerically.

This technique consists of an integration of the governing equations of mass, momentum, and energy on the individual cells within the computational domain to construct algebraic equations for each unknown dependent variable. The pressure and velocity are coupled using the SIMPLE (semi implicit method for pressure linked equations) algorithm which uses a guess-and-correct procedure for the calculation of pressure on the staggered grid arrangement. The second order upwind scheme is employed for the discretization of the model equations as it is always bounded and provides stability for the pressure-correction equation. Fluent solves the linear systems resulting from discretization schemes using a point implicit (Gauss–Seidel) linear equation solver in conjunction with an algebraic multigrid method. During the iterative process, the residuals were carefully monitored. For all simulations performed in the present study, converged solutions were considered when the residuals resulting from iterative process for all governing equations (5)–(10) were lower than 10^{-6}.

IV. Results And Discussions

In order to validate the computational model, the numerical results were compared with the theoretical data available for the conventional fluids. The Nusselt number for the fully developed turbulent flow for PG/water is compared with the correlation given by:

Maiga et al. [7] equation for nanofluid:

$$Nu = 0.085\ Re^{0.71}\ Pr^{0.35} \quad (11)$$

Pak and Cho [1998] equation for nanofluid [9]:

$$Nu = 0.021\ Re^{0.8}\ Pr^{0.5} \quad (12)$$

Bejan [22] equation for nanofluid:

$$Nu = 0.012\ (Re^{0.87} - 280)\ Pr^{0.4} \quad (13)$$

Dittus–Boelter equation for nanofluid:

$$Nu = 0.023\ Re^{0.8}\ Pr^{0.4} \quad (14)$$

The Darcy friction factor given by Blasius is presented as Eq. (15) from White [1991],[23].

$$f = 4\ C_f = 4\ (0.079\ Re^{-0.25}) \quad (15)$$

Fig.1 displays the comparison of Darcy friction factor from Blasius formula and computed values from the present simulations. An excellent agreement is observed with maximum deviation and average deviation of computed values from theoretical equation being 2.7 and 1.9%, respectively, over the range of Reynolds numbers studied.

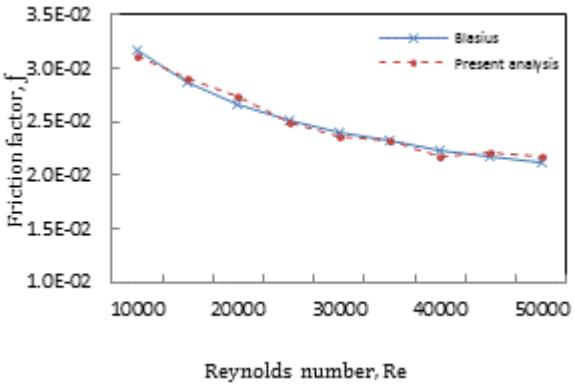

Fig. 1 Comparison of Darcy friction factor by Blasius and computed values for PG/water in turbulent regime.

A. Effect of nanoparticles volume concentration on the heat transfer coefficient

Fig.2 shows comparison of computed heat transfer coefficient from the present simulations for a PG/Water with other correlations, the deviation of computed values from theoretical equation with present analysis being 13%, and that is good agreement. It clearly evident from the Fig. 3 that heat transfer coefficient increases with volume concentration as well as Reynolds number. So, the higher heat transfer rates are possible at higher volume concentration of the nanofluid.

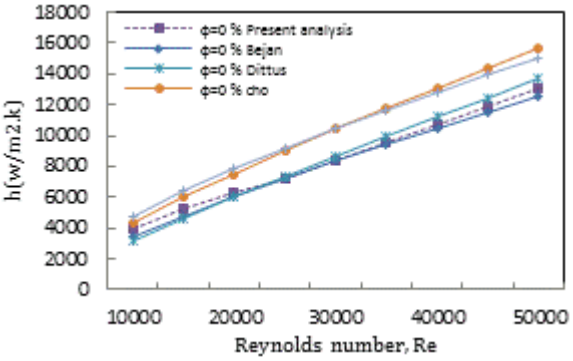

Fig.2. Comparison between the computed values of heat transfer coefficient and other equation for PG/water.

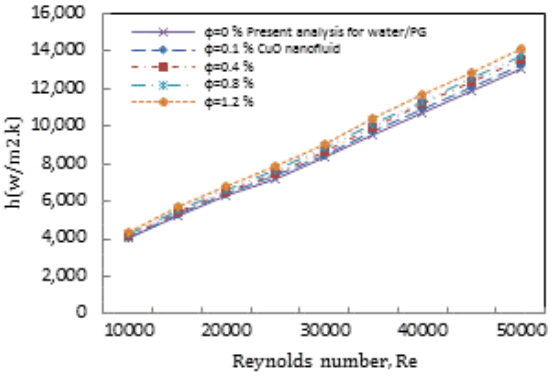

Fig.3. The influence of CuO volume concentration on the heat transfer coefficient over a range of Reynolds number.

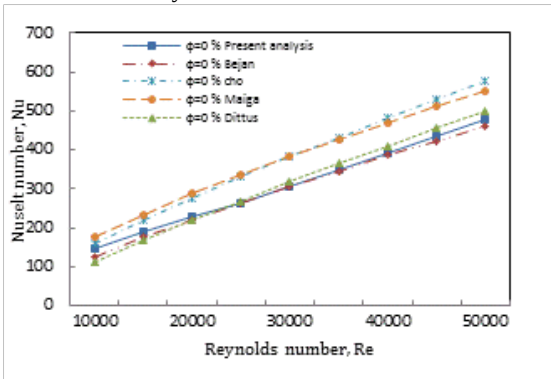

Fig.4. Comparison between the computed values of Nusselt numbers and other equation for PG/water

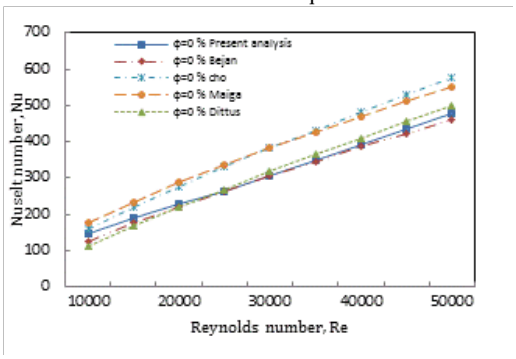

Fig.5 Comparison of Nusselt number for CuO (0.4%) in PG/water with other correlations

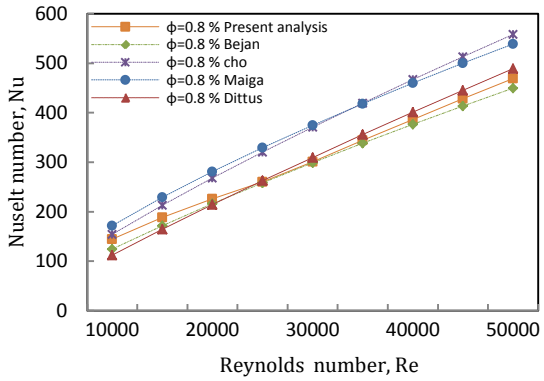

Fig.6 Comparison of Nusselt number for CuO (0.8%) in PG/water with other correlations

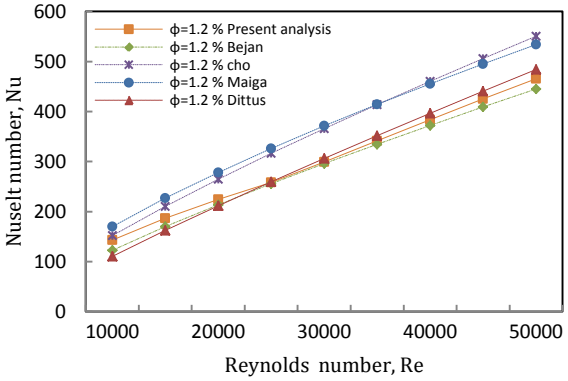

Fig.7 Comparison of Nusselt number for CuO (1.2 %) in PG/water with other correlations

B. Effect of nanoparticle volume concentration on the Nusselt number

Fig. 4-7 show the comparison of computed Nusselt number from our simulations for a CuO (from 0.1% to 1.2%) volume concentration nanofluid with other correlations. It clearly shows from the figure that Nusselt number increases with volume concentration as well as Reynolds number. So, the higher heat transfer rates are possible at higher volume concentration of the nanofluid.

C. Effect of nanoparticles volume concentration on the Stanton number and ratio of Nusselt number to Prandtl number

Fig.8 displays the comparison of computed Stanton number from our simulations for a PG/Water with other correlations. The Stanton number outcome from our result is near to theoretical equation

Fig.10 displays the influence of CuO volume concentration on the ratio of Nusselt number to Prandtl number over a range of Reynolds numbers. When the value of volume concentration increases this ratio increases and at higher Reynolds numbers the ratio of Nusselt number to Prandtl number increase.

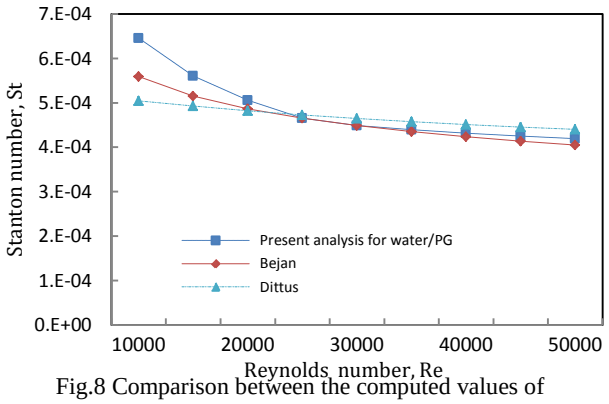

Fig.8 Comparison between the computed values of Stanto numbers and other equation for PG/water

Fig.8 displays the influence of CuO volume concentration on the Stanton number over a range of Reynolds numbers. It clearly shows from the figure, the Stanton number increases with volume concentration and decrease with increasing of Reynolds number. So, the higher The Stanton numbers are possible at higher volume concentration of the nanofluid. The Stanton number determine the ratio between the convection heat transfer flux at the interface and the thermal capacity of the fluid, so with adding the nanoparticles into fluid the Stanton number increase and the ratio between the convection heat transfer flux and the thermal capacity of the fluid increase.

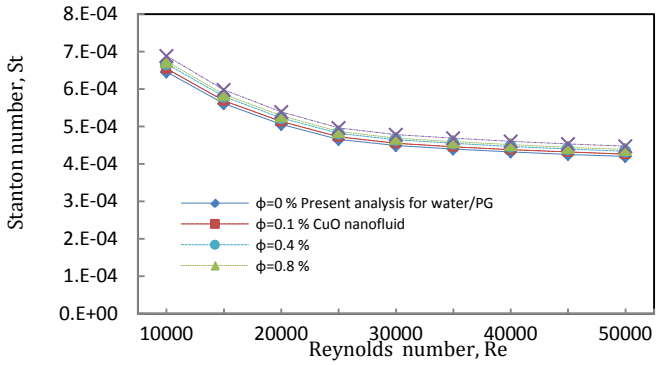

Fig.9. The influence of CuO volume concentration on the Stanton numbers over a range of Reynolds numbers.

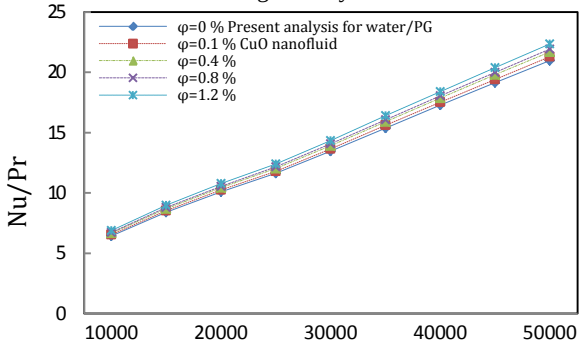

Fig.10 The influence of Cuo volume concentration on the ratio of Nusselt number to Prandtl number

V. CONCLUSION

In the present paper, steady state turbulent convection of Propylene glycol-water CuO nanofluid inside a circular tube was numerically investigated by means of finite volume method. Single phase constant thermophysical properties were taken into account in order to simulate the Propylene Glycol-Water CuO nanofluid. Results showed the useful contribution to the heat transfer provided by the inclusion of nanoparticles, in comparison to the case with just the base fluid. Heat transfer increased with the particles volume concentration and Reynolds number. The highest heat transfer rates, in absolute terms, were detected, for each concentration, in correspondence of the highest Reynolds number. A very good accord is found among the results of this study and the experimental correlation proposed by Pack and Cho [9] and Dittus–Boelter [10].

APPENDIX

Symbol	Quantity	Units
x	Distance from the inlet	m
L	Length of the tube	m
D	Diameter of the tube	m
T	Temperature	K
Q"	Heat flux	w/m2
V	Velocity	m/sec
Cp	Specific heat	J/kgK
k	Thermal conductivity	W/mK
h	Heat transfer coefficient	W/m2K
φ	Volume concentration	%
ρ	Density	kg/m3
μ	Viscosity	Pa s
Nu	Nusselt number	
Re	Reynolds number	
Pr	Prandt number	
f	Friction factor	
Cf	Skin friction coefficient	
St	Stanton number	

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