

Heat Transfer Enhancement by Using Nanofluids in Forced Convection Laminar Flows

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Abstract:

A numerical investigation by implementing ANSYS Fluent code to study forced convection confined flow with nanofluids. The flow is laminar and a uniform temperature is applied on the surface. The single-phase model approach has been adopted. Different particle volume concentrations, base fluids, nanoparticle materials and Reynolds numbers have been considered in order to investigate the hydrodynamic and thermal behaviors for nanofluids. The introduction of nanoparticle produces an increase of fluid bulk temperature because of the elevated thermal conductivity of nanofluids. The local and average heat transfer

coefficient increase for the nanofluids with Re . Also, they increase as volume fraction concentrations, thermal conductivity of nanoparticles materials and Pr of the base fluid. The results reveal that the required pumping power increases as well as the Reynolds number and particle concentration.

Key words : CFD - Forced convection - Confined Laminar flow - Nanofluids

Nomenclature

D Pipe diameter [m]

C_p Specific Heat

h Heat transfer coefficient [$w (m^{-2} K^{-1})$]

k Thermal conductivity [$w (m^{-1} K^{-1})$]

Nu Nusselt number

p Pressure [Pa]

Pr Prandtl number

Q Heat flux [$W m^{-2}$]

Re Reynolds number

T Temperature [K]

u x-component of velocity [$m s^{-1}$]

\dot{V} Volumetric flow rate [m^3/s]

Greek symbols

α Heat diffusivity [$m^2 s^{-1}$]

ϕ Nanoparticle concentration

ν Momentum diffusivity [$m^2 s^{-1}$]

ρ Density [kg / m^3]

μ Viscosity

Subscripts

o Base fluid

r r –coordinate

nf Nanofluid

p Nanoparticle

x Local

1.Introduction:

In many industrial applications such as power generation, heat exchangers, microelectronics, heating processes, cooling processes and chemical processes, the effectiveness of heat exchange processes are obstructed by the lower heat transfer properties of these common fluids as compared to most solids. It is obvious that solid particles having thermal

conductivities several hundred times higher than these conventional fluids must be used in the heat transfer applications. To improve thermal conductivity of a fluid, suspension of ultrafine solid particles in the fluid can be a creative idea. Choi, 1995 [1] at Argonne National Laboratory proposed the use of nanoparticles to enhance the thermal conductivity of liquids, and coined the term ‘nanofluids’ for the resulting mixtures. Compared with the existing techniques for enhancing heat transfer, the nanofluids show a great potential in increasing heat transfer rates in a variety of application cases, with incurring either little or no penalty in pressure drop. The main reasons may be listed as follows:

- The suspended nanoparticles increase the surface area and the heat capacity of the fluid.
- The suspended nanoparticles increase the effective thermal conductivity of the fluid.
- The interaction and collision among particles, fluid and the flow passage surface are intensified.
- The mixing fluctuation and turbulence of the fluid are intensified.
- The dispersion of nanoparticles flattens the transverse temperature gradient of the fluid.

Nanofluids are a new class of fluids engineered by dispersing nanometer-sized materials (nanoparticles, nanofibers, nanotubes, nanowires, nanorods, nanosheets, or droplets) in base fluids. Common base fluids include water, organic liquids (e.g. ethylene, tri-ethylene-glycols, refrigerants, etc.), oils and lubricants, bio-fluids, polymeric solutions and other common liquids. Materials commonly used as nanoparticles include chemically stable metals (e.g. gold, copper), metal oxides (e.g., alumina, silica, zirconia, titania), oxide ceramics (e.g. Al_2O_3 , CuO , TiO_2), metal

carbides (e.g. SiC), carbon in various forms (e.g., diamond, graphite, carbon nanotubes, fullerene) and functionalized nanoparticles. Much attention has been paid in the past decade to this new type of composite material because of its enhanced properties and behavior associated with heat transfer, mass transfer, wetting and spreading and antimicrobial activities and the number of publications related to nanofluids increases in an exponential manner

The number of theoretical and experimental investigations on convective heat transfer in confined flows with nanofluids is growing. Some experimental investigations[2-7] have revealed that the nanofluids have remarkably higher thermal conductivities than those of conventional pure fluids and shown that the nanofluids have great potential for heat transfer enhancement. Alumina (Al₂O₃), Titania (TiO₂) and copper oxide (CuO) are the most common and inexpensive nanoparticles used mixed with water as a base fluid.

Nanofluids are more suits for practical application than the existing techniques for enhancing heat transfer by adding millimeter and/or micrometer-sized particles in fluids. It incurs little or no penalty in pressure drop because the nanoparticles are so small that the nanofluid behaves like a pure fluid. Moreover, also the number of numerical studies by implementing CFD programs on nanofluids is growing, and the analysis can be carried out by using two approaches. It is possible to consider that the continuum assumption is still valid for fluids with suspended nanosize particles at low volume fractions up to 10 % volume fraction or to adopt two-phase models in order to describe both the fluid and the solid phase. The single-phase model with physical and thermal properties, all assumed to be constant with temperature, was employed in [8–11]. The advantages

of adopting nanofluids with respect to the heat transfer mechanism were discussed in, but it was also found that the presence of nanoparticles led to significant effects on growing wall shear stress and pumping power for heated tubes in laminar and turbulent regime.

Therefore, theoretical and experimental research works is needed to clearly understand and accurately predict the hydrodynamic and thermal characteristics of nanofluids.

Problem Formulation:

Assuming the flow is steady, incompressible, Newtonian and laminar with no viscous heating, The nanoparticles are assumed to have a uniform shape and size. Moreover, it is assumed that both the fluid phase and nanoparticles are in thermal equilibrium state and they flow at the same velocity. The governing equations are:

$$\frac{1}{r} \frac{\partial(r u_r)}{\partial r} + \frac{\partial u_x}{\partial x} = 0 \quad (1)$$

$$u_r \frac{\partial u_r}{\partial r} + u_x \frac{\partial u_r}{\partial x} = -\frac{1}{\rho} \frac{\partial P}{\partial r} + \nu \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial u_r}{\partial r} \right) - \frac{u_r}{r^2} + \frac{\partial^2 u_r}{\partial x^2} \right] \quad (2)$$

$$u_r \frac{\partial u_x}{\partial r} + u_x \frac{\partial u_x}{\partial x} = -\frac{1}{\rho} \frac{\partial P}{\partial x} + \nu \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial u_x}{\partial r} \right) + \frac{\partial^2 u_x}{\partial x^2} \right] \quad (3)$$

$$u_r \frac{\partial T}{\partial r} + u_x \frac{\partial T}{\partial x} = \alpha \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial x^2} \right] \quad (4)$$

Nanofluid Properties:

The base fluid is a homogeneous mixture of base fluids (water, heavy oil and ethylene-glycol) mixed with nanoparticles of oxide ceramics (Al₂O₃, TiO₂ and Cu) at different concentrations by volume (3, 6 and 9 %). Following the effective medium theory [12] to evaluate the thermal conductivity of the nanofluid as follows.

$$k_{nf} = k_o + \frac{3 \phi k_o (k_p - k_o)}{\phi (k_p - k_o) + k_p + 2 k_o} \quad (5)$$

The density is evaluated using volume-weighted average of the liquid and particle densities.

$$\rho_{nf} = \phi \rho_p + (1 - \phi) \rho_o \quad (6)$$

Assuming thermal equilibrium between the particles and the surrounding fluid, the nanofluid specific heat capacity per unit mass of nanofluid, that is, the nanofluid specific heat, is :

$$(C_p)_{nf} = \frac{\phi (\rho C_p)_p + (1 - \phi) (\rho C_p)_o}{\phi \rho_p + (1 - \phi) \rho_o} \quad (7)$$

Einstein (1956) was the first to calculate the effective viscosity of a suspension of spherical solids using the phenomenological hydrodynamic,

Batchelor [13] proposed a similar correlation considering the nanoparticle Brownian motion and their interaction:

$$\mu_{nf} = (1 + 2.5 \phi + 6.5 \phi^2) \mu_o \quad (8)$$

Numerical Procedure :

The Computational domain of circular channel is represented in two dimensional (2D) form by a rectangle and displayed in Fig. (1). The geometry consists of a wall, a centerline, and an inlet and outlet boundaries. The radius, R and the length, L of the pipe are specified in the figure. The boundary conditions are specified on the geometry where the velocity inlet and pressure outlet are specified. At the wall a no slip conditions and constant wall temperature are specified.

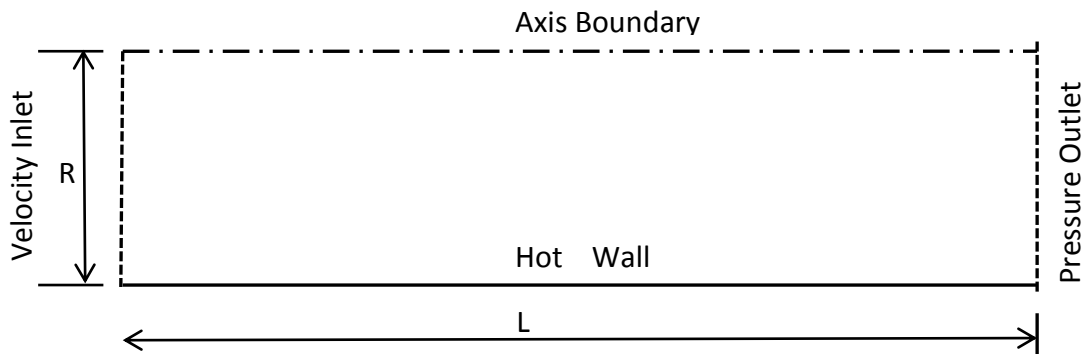


Fig. (1) Geometry and Boundary conditions

The axisymmetric Navier-Stokes and energy equations were solved using ANSYS 17. A structured mesh was built. The mesh was nonuniform in order to optimize distribution in the boundary layer and entrance region where relatively higher gradients are expected. A snap shot of the mesh in the entrance region is shown in Fig. (2). The simulation was carried out using SIMPLE algorithm and second-order differencing schemes. A second order upwind scheme is chosen for energy and momentum equations. The SIMPLE coupling scheme is chosen to couple pressure and velocity. The convergence criteria of 10^{-5} are assumed for the residuals of the velocity components and energy. The number of iterations is set up and iterations start. The iterations continue till the convergence is reached and convergence history as shown in Fig (3), for one of the cases of nanofluid calculations

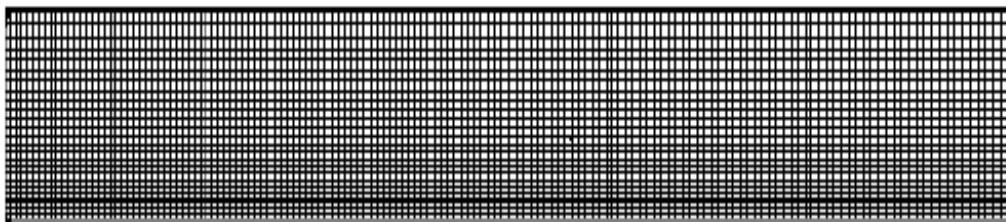


Fig. (2) Snap shot of the mesh

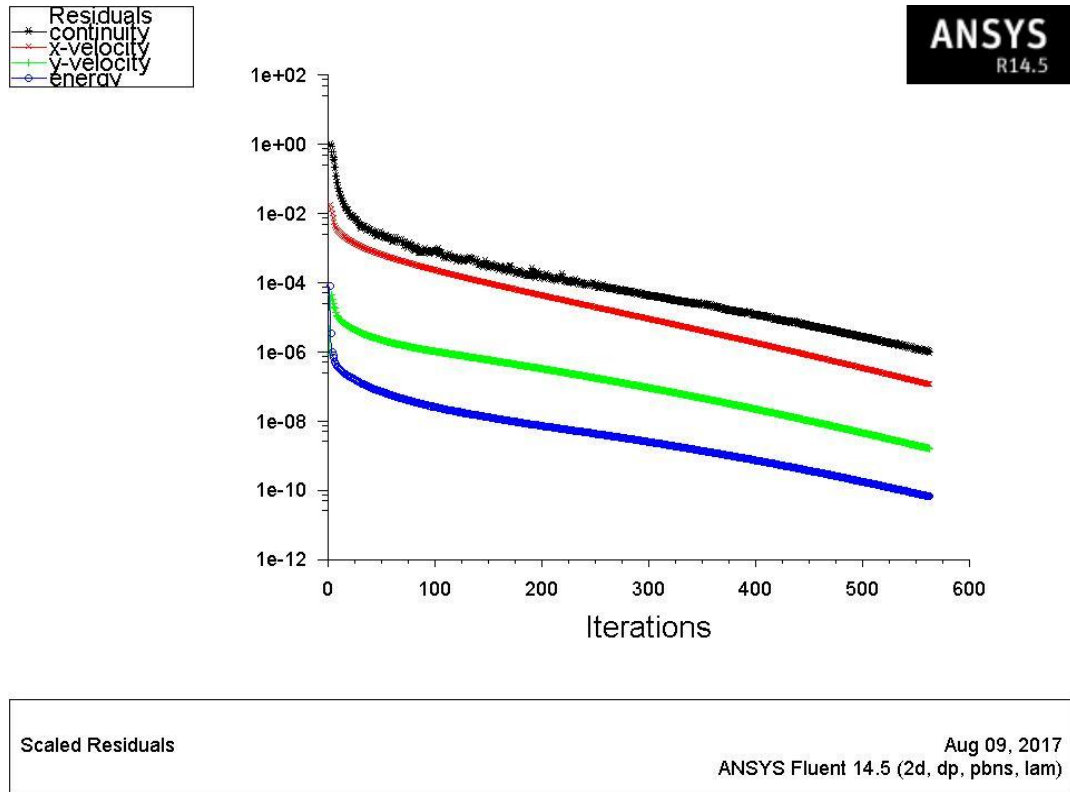


Fig. (3) Convergence history

Validation Analysis:

There are mainly two sources of uncertainty in CFD, namely modeling and numerical errors [14]. Numerical uncertainty can be approximated through grid independence. Numerical uncertainty has two main sources, namely truncation and round-off errors. Higher order schemes have less truncation error, comparison between the numerical modeling and the analytical solution is depicted in Fig. (4) where friction coefficient has been plotted against Reynolds number for pure water and compared with the analytical equation $f=16/Re$ for laminar flow

conditions. The grid independence is also verified and shown in Fig. (5). Therefore, both the numerical and modeling errors are considered negligible.

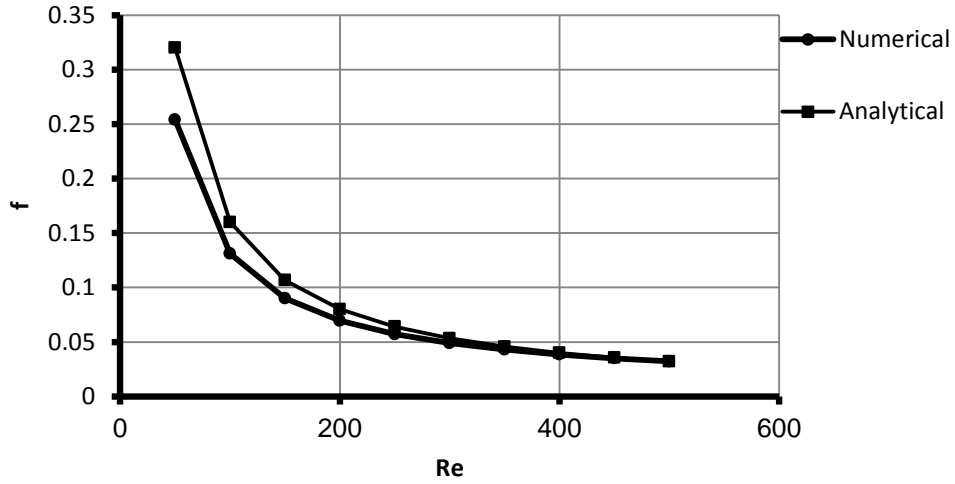


Fig. (4) Validation with analytical results

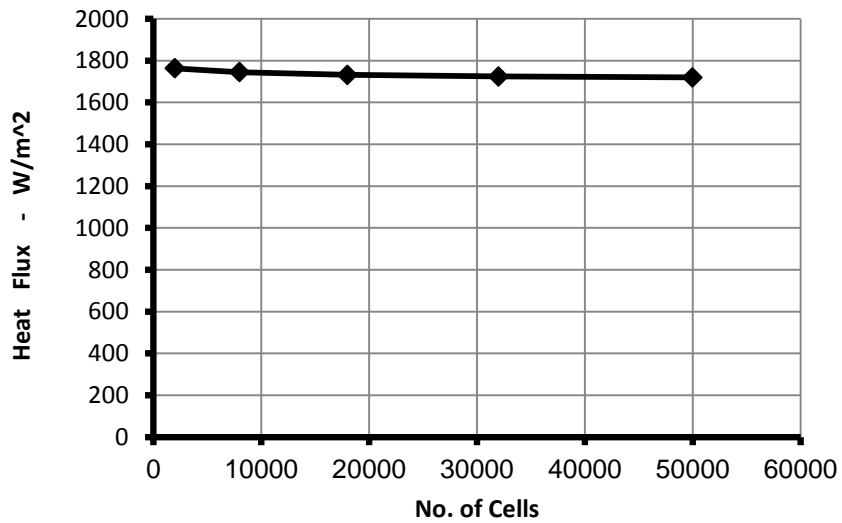


Fig. (5) Grid independence test results

Results and Discussion:

A computational analysis of a two-dimensional model, regarding a confined forced convection flow with nanofluids, is considered in order to evaluate the thermal and fluid-dynamic performances. The single-phase model approach is adopted. The ranges of the considered Reynolds numbers, base fluids, nanoparticle materials and volume fractions are given follows:

- i. Reynolds number (Re): 100, 200, 300, 400 and 500;
- ii. Base fluids are water, engine oil and ethylene glycol;
- iii. Nanoparticle materials, copper (Cu), Alumina (Al_2O_3) and Titania (TiO_2)
- iv. Particle concentrations (ϕ): 0%, 3%, 6%, and 9% by volume

Effect of Particle Volume Concentration :

From the experimental results the general trend is clear: thermal conductivity enhancement increases with increase particle volume concentration. Fig. (6) and Fig. (7) describe the local convective heat transfer coefficient distributions along the hot surface at $\text{Re} = 50$, for $\phi = 0\%$, 3% , 6% , and 9% . Convective heat transfer coefficient of nanofluid increases with increase in its concentrations. This increase in heat transfer rate is mainly contributed by increase in thermal conductivity of nanofluid by addition of nanoparticles and increased turbulence in the flow. Higher the concentrations of nanoparticles in the base fluid it increases its thermal convection and hence less resistance for heat transfer.

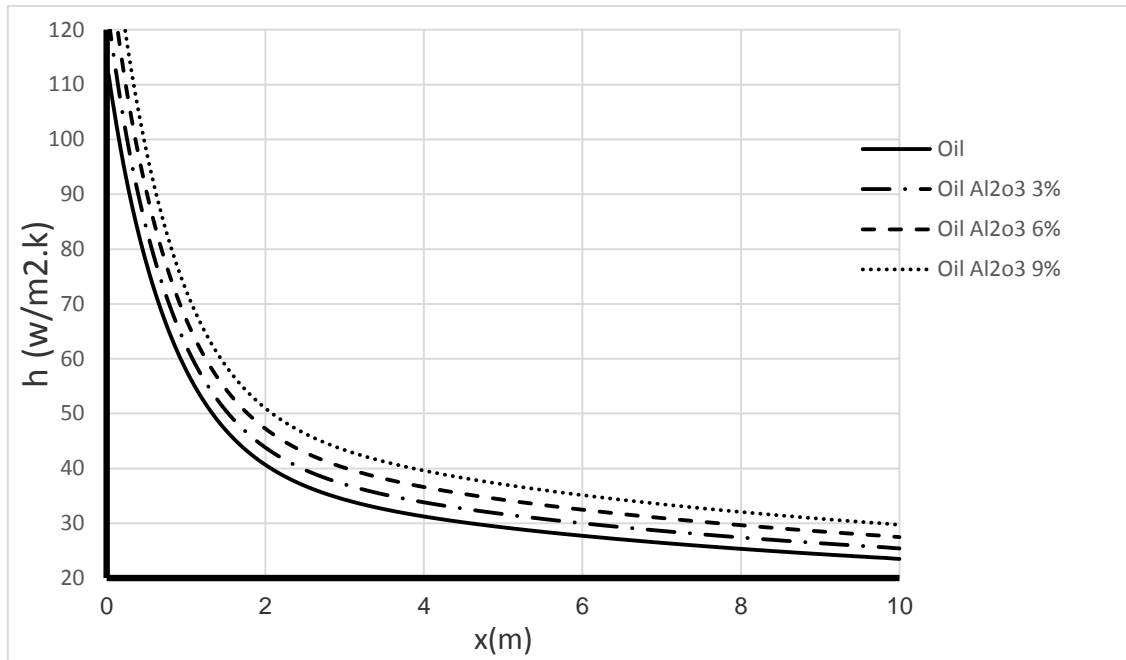


Fig. (6) Local heat transfer coefficient for Oil nanofluids

The values of convective heat transfer coefficient increases with increase in flow rate of nanofluid i.e. Reynolds number of flow as shown in Fig. (7). Convective heat transfer coefficients for nanofluids are more than that of base fluid water. For water and its nanofluids the enhancement reaches to 21% for 9% volume fraction at $Re = 500$.

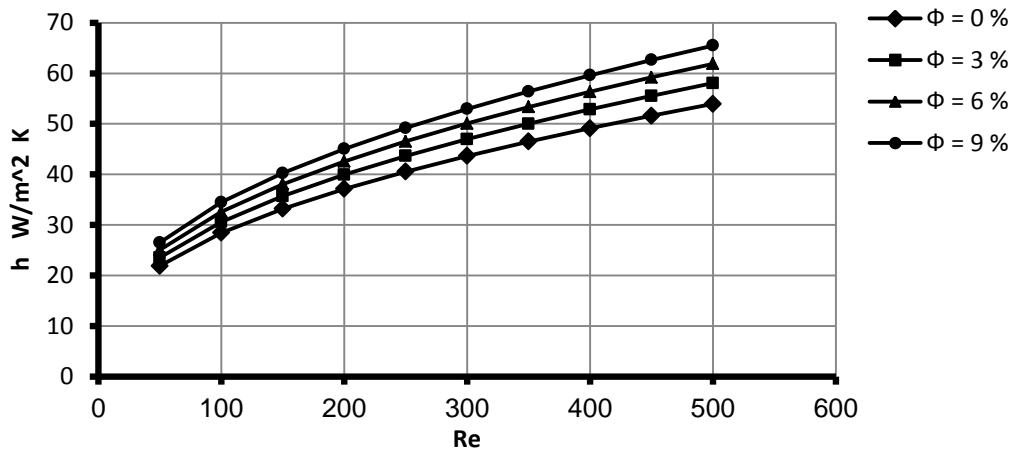


Fig. (7) Average heat transfer coefficients for water/ Al_2O_3 nanofluids

Effect of Base Fluid Material :

The results show increased thermal conductivity enhancement for poorer (lower thermal conductivity) heat transfer fluid. The results of forced convection process of nanofluids with volume fraction $\phi = 9\%$, for different base fluids are shown in Fig. (8).

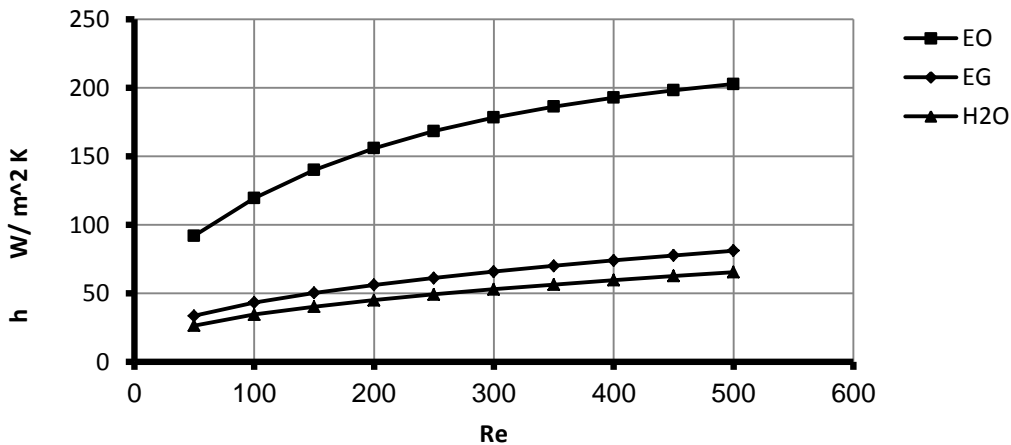


Fig. (8) Average heat transfer coefficients for Al_2O_3 with different base fluids at $\phi = 9\%$

It can be observed that the least enhancement for water which is the best heat transfer fluid with the highest thermal conductivity of the fluids compared. This can be explained as the nanoparticles and high-Prandtl number base fluid such as engine oil and ethylene glycol which has $Pr = 13488$ and $Pr = 150$ respectively, could significantly increase the heat transfer performance for nanofluids

Effect of Particle Material :

Plotting the Average heat transfer coefficient versus Re as shown in Fig. (9), the results are for water and different nanoparticles materials at volume fraction $\phi = 9\%$. It is assumed that the size and the shape of the nanoparticles is the same during all calculations. it can be seen that that the heat transfer enhancement increases with the presence of nanoparticles and this increases depend on nanoparticle material thermal conductivity, this enhancement is more for metals which is Cu particles than metal oxides ; Al_2O_3 and TiO_2 .

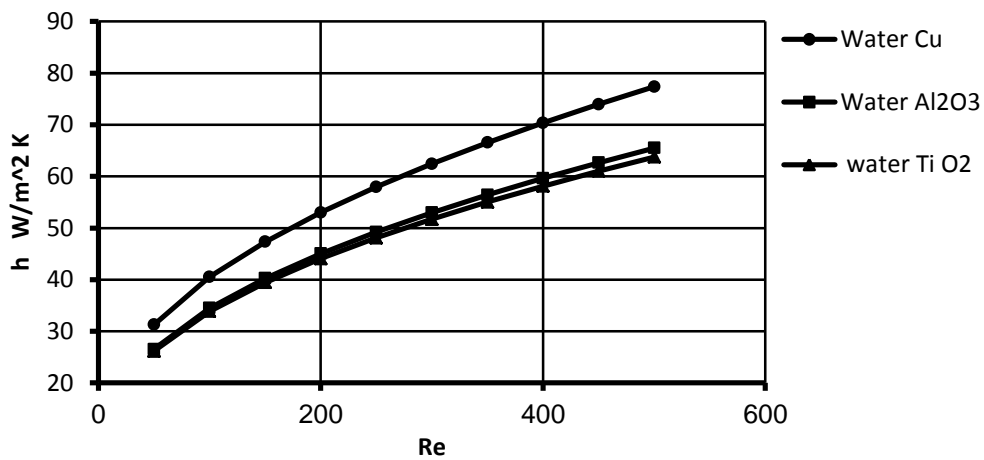


Fig. (9) Average heat transfer coefficients for water with different nanoparticles materials at $\phi = 9\%$

Pumping Power Requirements:

The numerical calculations of the average friction factor results are used in calculation of pressure drop. Once the pressure drop (or head loss) is known, the required pumping power to overcome the pressure loss is determined from by the relation $PP = \dot{V} \Delta P$

The pumping power ratio referred to the base fluid values is described in Fig. (10) to the water cases nanofluids with Al_2O_3 versus Reynolds number at different volume concentrations. It is observed that the ratio (PP_{nf}/PP_f) profiles tend to increase as the volume concentration grows while very little dependence on Re where the results indicate that pumping power ratio is equal to 1.22, 1.15, and 1.22.0 for $\phi = 3\%$, 6%, and 9%, respectively. Similarly, the pumping power ratio plotted for different nanoparticles materials as shown in Fig. (11). Its profiles tend to increase with the nanofluid density while less dependence with Re.

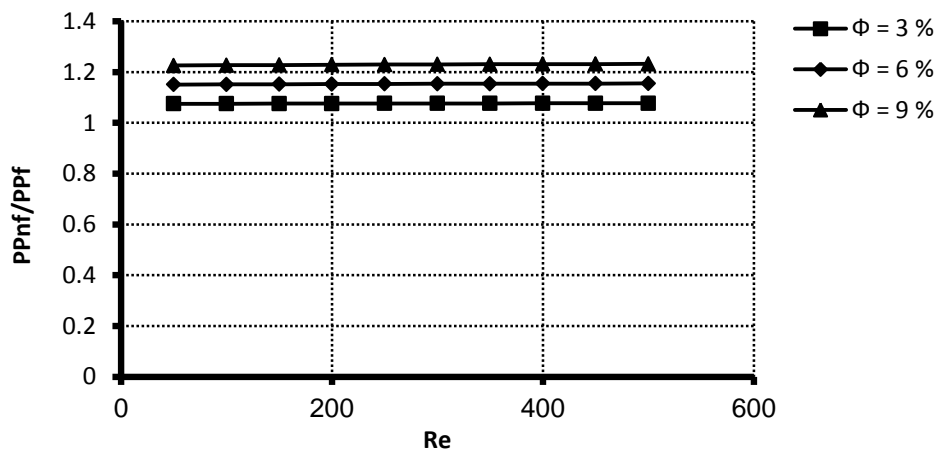


Fig (10) Pumping power profilesas for water/ Al_2O_3 for different concentrations

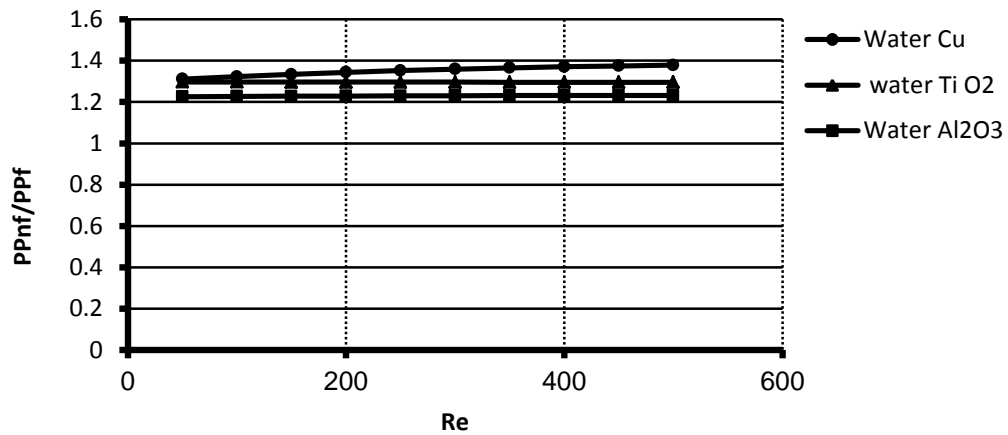


Fig (11) Pumping power profiles as for $\phi = 9\%$ for different nanoparticles materials with water.

Conclusion:

A steady state computational fluid dynamics (CFD) models was simulated by ANSYS Fluent 17. The effect of different parameters on heat transfer enhancement by nanofluids are investigated. The use of nanofluids as the heat transport medium in the channel were found useful in laminar flow conditions. For nanofluids, increasing volume fraction and Re number will enhance the convective heat transfer performance with very limited penalties in increased pumping power requirement. Results showed that the high thermal conductivity of base fluid the lower heat transfer enhancement resulted and the nanoparticle material has the least effect on heat transfer enhancement by nanofluids.

References:

1. Choi, S.U.S., “ Enhancing thermal conductivity of fluids with nanoparticles” In: *Proceedings of the 1995 ASME International Mechanical Engineering Congress and Exposition, San Francisco, CA, USA.* 66, 99-105, (1995).
2. Ding, Y., Chen, H., He, Y., Lapkin, Y., Yeganeh, M., Šiller, L. Butenko, Y. V., “Forced convective heat transfer of nanofluids”. *Advanced Powder Technol.*, 18(6), pp.813– 824, (2007).
3. Wang, Xiang-Qi, Arun, S. and Mujumdar, “Heat transfer characteristics of nanofluids: a review”. *International Journal of Thermal Sciences.* 46, 119, (2007).
4. Gherasim, I., Roy, G., Nguyen, C. T. and Vo-Ngoc, D., “Experimental investigation of nanofluids in confined laminar radial flows”. *International Journal of Thermal Sciences.* 48, 1486 – 1493, (2009)
5. Huminic, G.; Huminic, A., “Heat transfer characteristics in double tube helical heat exchangers using nanofluids” . *Int. J. Heat Mass Tran.*, 54, 4280-4287, (2011).
6. Leong, K.Y.; Saidur, R.; Mahlia, T.M.I.; Yau, Y.H. “Modeling of shell and tube heat recovery exchanger operated with nano fluid based coolants”. *Int. J. Heat and Mass Transfer*, 55, 808-816, (2012).
7. Shelke, D. B., and Hole, J. A. “ Heat transfer enhancement of tube in tube heat exchanger using Cu/H₂O nanofluid under turbulent flow” .

- VSRD International Journal of Mechanical, Civil, Automobile and Production Engineering, Vol. 3 No. 3 March (2013).*
8. Rennie, T. J., Raghavan, V. G. S., “Numerical Studies of a Double-Pipe Helical Heat Exchanger”. *Applied Thermal Engineering*, 26, 11-12, pp. 1266-1273,(2006).
 9. Abu-Nada, E., “Application of nanofluids for heat transfer enhancement of separated flows encountered in a backward facing step” . *International Journal of Heat and Fluid Flow*, 29, no. 1, 242–249, (2008).
 10. Lotfi, R.; Saboohi, Y.; Rashidi, A.M. Numerical study of forced convective heat transfer of Nanofluids: Comparison of different approaches. *Int. J. Commun. Heat Mass Trans.*, 37, 74-78, (2010)
 11. Fard, M. H., Talaie, M. R., and Nasr, S., “ Numerical and experimental investigation of heat transfer of ZnO/H₂O nanofluid in the concentric tube and plate heat exchangers’ . *J. of Thermal Science*, Vol. 15, No. 1, pp. 183-194, (2011).
 12. Keblinski P, Prasher R, Eapen J, Thermal conductance of nanofluids: *Journal of Nanoparticle Research*, Vol. 10, pp. 1089-1097, (2008).
 13. Batchelor, G. “The effect of Brownian motion on the bulk stress in a suspension of spherical particles,” *Journal of Fluid Mechanics*, vol. 83, no. 1, pp. 97–117, 1977.

14. Stern F, Wilson R, Coleman H, and Paterson E, “*Verification and Validation of CFD Simulations*”, Iowa Institute of Hydraulic Research IIHR 407, College of Engineering, University of Iowa, Iowa City, 3, 1999.