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Numerical Heat Transfer Performance of Water-Based Graphene Nanoplatelets

Ahmad Amiri, Hamed K. Arzani, S. N. Kazi, B. T. Chew

***Abstract*—**Since graphene nanoplatelet (GNP) is a promising material due to desirable thermal properties, this paper is related to the thermophysical and heat transfer performance of covalently functionalized GNP-based water/ethylene glycol nanofluid through an annular channel. After experimentally measuring thermophysical properties of prepared samples, a computational fluid dynamics study has been carried out to examine the heat transfer and pressure drop of well-dispersed and stabilized nanofluids. The effect of concentration of GNP and Reynolds number at constant wall temperature boundary condition under turbulent flow regime on convective heat transfer coefficient has been investigated. Based on the results, for different Reynolds numbers, the convective heat transfer coefficient of the prepared nanofluid is higher than that of the base fluid. Also, the enhancement of convective heat transfer coefficient and thermal conductivity increase with the increase of GNP concentration in base-fluid. Based on the results of this investigation, there is a significant enhancement on the heat transfer rate associated with loading well-dispersed GNP in base-fluid.

***Keywords*—**Nanofluid, turbulent flow, forced convection flow, graphene, annular, annulus.

I. Introduction

FLUIDS flow in the annular ducts and their convective heat transfer are important phenomena in the engineering systems due to their technological applications such as cooling core of nuclear reactors, electrical gas-insulated transmission lines, thermal insulation, gas-cooled electrical cables, cooling systems, compact heat exchangers, cooling of electronic devices, boilers, solar energy systems, aircraft fuselage insulation to underground electrical transmission cables and thermal storage systems [1]-[4]. As a result, studies on the heat transfer enhancement in annular shape pipes are essential [5].

Nanofluid is defined as a new kind of fluids with metallic nanoparticle or carbon nanostructure suspended in base-fluid [6]-[10]. Heat transfer of nanofluids can be the functions of dimension, nanoparticles' properties, volume concentration of nanoparticles etc. [11]-[14]. According to the experimental investigations [8], [15]-[26], nanofluids have shown a promising potential for augmentation of energy transfer and also have higher thermal conductivities in comparison to the base-fluids. Owing to the nanofluids characteristics, many kinds of industries including automotive radiator systems, computer processing cooling equipment, home heating and cooling appliances, power plant cooling systems can employ the suggested technique.

As a pioneer, Chol in 1995 [27] used nanofluid to increase the heat transfer rate. After that, many studies concentrated on the thermophysical and thermal properties of nanofluids. To be cost-effective, a majority of researchers focused on the modelling of the effective thermal parameters such as heat transfer coefficient and thermal conductivity in the presence of nanofluids. To address this issue, two methods of single-phase or two-phase were employed to calculate the convective heat transfer coefficient of nanofluids, which both can be resulted in validated results. Commonly, the single-phase approach constructs based on an assumption of having the same velocity for both nanoparticles and base-fluid. In addition, there is thermal equilibrium between them to facinate the method and decreasing computational time. However, finding some valid correlations for measuring thermophysical properties of nanofluids in single-phase is essential in this method [28]-[36]. Unfortunately, the lack of appropriate agreement between results obtained by single-phase simulation and experiments does not permit this method to be accepted as a dominant technique, which is caused by low-accuracy of correlations to anticipate the behavior of both nanoparticles and base-fluid. On the other hand, some parameters in nanofluids like Brownian motion, concentration, and sedimentation of particles, may have a direct effect on flow regime and subsequently the extent of heat transfer rate [37]. To solve the problems with one-phase approach, two-phase approach was introduced as a novel method with the capability of investigation of both solid and liquid phases, showing a great agreement with theoretical and experimental results. Due to the high validity of two-phase method, many studies on multiphase flow utilized the "Mixture Theory" for minimizing the percentage of error over simulation [38]-[42]. Note that, unlike one-phase method, this method used underlying theory, and different phases can be mathematically defined as a continuum. To address this issue, Lotfi et al. [43] compare single-phase method with two-phase Eulerian and two-phase mixture methods for simulation of the flow behavior in the presence of nanofluids. Consistent with their results, two phase mixture approaches can be considered as an accurate method in a straight pipe as compared with the other two approaches. Accordingly, some researchers were employed the above-mentioned method for simulating the behavior of flow and heat transfer in the presence of different nanofluids [31], [32], [44]-[46].

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The objective of the present study is abstracted in investigation of numerical simulation of the convective heat transfer in an annular heat exchanger. To realize this goal appropriately, two-phase mixture model is employed. The obtained results by simulation with two-phase method was validated with the analytical results and they are confirmed. Then, the nanofluids flow in a three dimensional annular pipe is investigated for different mass fractions and Reynolds numbers. As a result, Nusselt number profiles, friction factor and the performance index are measured for synthesized nanofluids.

II. Analysis

Forced convection heat transfer of the EG-water mixture as well as ethylene glycol-treated Graphene Nanoplatelets-based water-ethylene glycol nanofluids (EGNP-WEG) were compared, and the thermophysical properties of the synthesized samples were obtained from our recent work [6]. Then, the EGNP-WEG coolants in a horizontal annular tube with a uniform heat flux at the inner wall has been considered. Fig. 1 shows the geometry of our study which consists of a straight annular pipe with outer radius of r_o (4 mm), inner radius of r_i (2 mm), and length of L (60 mm). The size of r_o is exactly two times of r_i and the channel length (L) is 60 times of the hydraulic diameter (D_h) to attain the fully developed region at the outlet. The turbulent region with steady state and incompressible flow was considered as the initial condition for nanofluid. Fluid properties are assumed to be constant over tube due to the mean temperature of fluid does not changed more than 2 degrees.

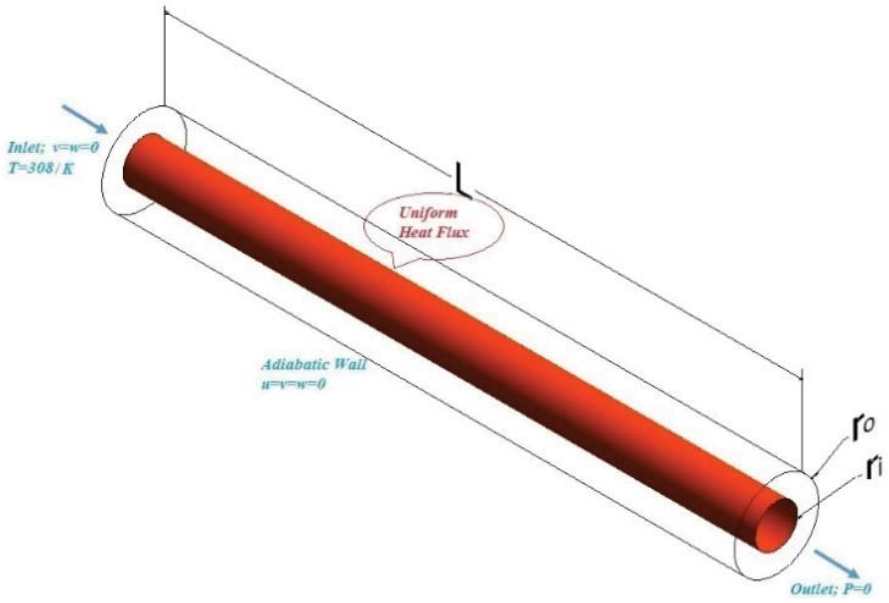


Fig. 1 Geometrical configuration and boundary conditions of the present study

The present numerical simulation employs the mixture model by assuming that two phases are interpenetrating, meaning that there is a velocity vector field of the primary phase and also a velocity vector field of the secondary phase. Within any control volume, each phase has its own volume fraction, and the connection between phases is strong, so nanoparticles closely follow the base-fluid flow. The mixture method applications and its accuracy in calculation for nanofluids have been showed by several researchers such as [43]-[47], [32].

As an alternative to the application of the governing equations for each phase, the continuity, momentum, and fluid energy equations for the mixture are employed. By looking at the forced convection heat transfer in the turbulent region for incompressible and Newtonian fluid, the governing equations can be written as follows [48]:

1. a). Continuity Equation

$$\nabla.\left(\rho_{eff}\overline{V}\right)=0 \tag{1}$$

2. Momentum Equations

$$\nabla.(\rho_{eff}\overline{V}\overline{V})=-\nabla\overline{P}+\mu_{eff}\nabla^2\overline{V}-\rho_{eff}\nabla.(\overline{v'v'}) \tag{2}$$

3. Conservation of Energy

$$\nabla.(\rho_{eff}C_{p,eff}\overline{V}\overline{T})=\nabla.((k_{eff}+k_t)\nabla\overline{T}) \tag{3}$$

In the above equations, the symbols $\overline{V}$, $\overline{P}$ and $\overline{T}$ represent the time averaged flow variables, while the symbol v' represents the fluctuations in the velocity. The term of $\rho_{eff}\nabla.(\overline{v'v'})$ in the momentum equations illustrates the turbulent shear stress. The terms of k_{eff} and k_t represent the

effective molecular conductivity and the turbulent thermal conductivity, respectively.

To model the flow in the turbulent regime, the standard *k*-ε model can be employed based on the Launder and Spalding study [49], which is as follows:

$$\nabla.(\rho_{eff} kV) = \nabla.[(\frac{\mu_t}{\sigma_k})\nabla(k)] + G_k - \rho_{eff}\varepsilon \quad (4)$$

$$\nabla.(\rho_{eff} \varepsilon V) = \nabla.[\frac{\mu_t}{\sigma_\varepsilon}\nabla\varepsilon] + \frac{\varepsilon}{k}(C_{1\varepsilon}G_k - C_{2\varepsilon}\rho_{eff}\varepsilon) \quad (5)$$

$$G_k = \mu_t(\nabla V + (\nabla V)^T),\ \mu_t = \rho_{eff} C_\mu \frac{k^2}{\varepsilon} \quad (6)$$

$$C_\mu = 0.09, \sigma_k = 1.00, \sigma_\varepsilon = 1.30, C_{1\varepsilon} = 1.44, C_{2\varepsilon} = 1.92 \quad (7)$$

where μ_{eff} and μ_t are the effective viscosity of nanofluid and coefficient of viscosity in turbulent regime, respectively.

A. Numerical Implementation

Herein, the numerical method available in the commercial CFD package of ANSYS-Fluent, V15 has been used. Fluent uses a finite volume approach to convert the governing partial differential equations into a system of discrete algebraic equations. Based on the discretization methods, a second-order upwind scheme is selected for the momentum, turbulent kinetic energy and turbulent dissipation rate equations, whereas the second order upwind for energy equation is selected. For two-phase calculations, the phase momentum equations with the shared pressure are solved in a coupled and segregated fashion. The phase coupled SIMPLE (PC-SIMPLE) algorithm is employed for the pressure-velocity coupling. PC-SIMPLE is an extension of the SIMPLE algorithm to multiphase flows. The scaled residuals for the velocity components and energy are equal to 10-8 and 10-9, respectively.

A structured non-uniform grid distribution has been used to discretize the computational domain. Finer grids have been used close to the inner wall where the temperature gradients are high. Several different grid distributions have been tested to ensure that the calculated results are grid independent. It is shown in Fig. 2 that increasing the grid numbers does not change significantly the Nusselt numbers. Therefore, the total grid points and the elements employed in the whole tube are 798304 and 757500, respectively (x=3000 r=100, Θ=100 elements).

B. Validation

Heat transfer enhancement of the mixture of water-EG flow in a horizontal annular tube with uniform heat flux at the inner wall has been simulated.

The Nusselt numbers have been calculated by the ANSYS-Fluent and the analytical solutions are presented in Fig. 3. The calculated Nusselt via the Dittus-Boelter and Gnielinski correlations shows a significant agreement with numerical results, which the maximum error of 5.3% is obtained. As a result, the numerical method is reliable when it can predict the mixed convection flow in an annular pipe in the presence of nanofluid.

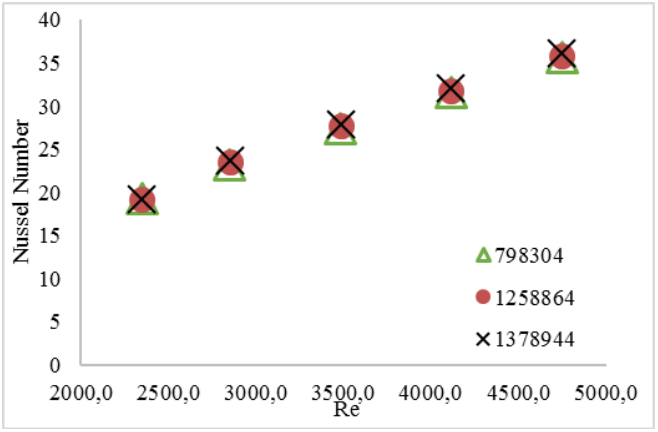


Fig. 2 Comparison of Nusselt numbers versus Reynolds numbers for base-fluid at three different grid distributions

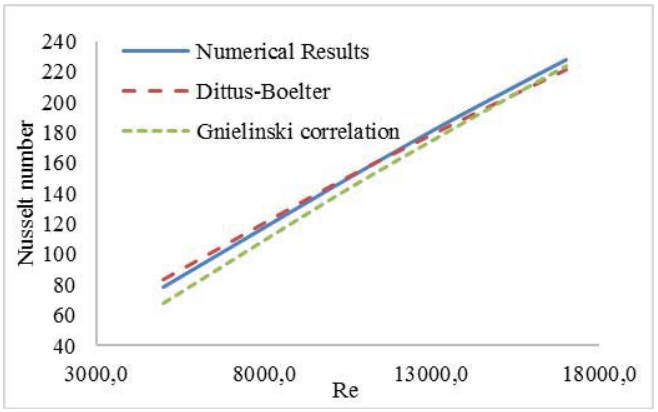


Fig. 3 Nusselt profiles for various Reynolds numbers through annular heat exchanger obtained by numerical two-phase method and its comparison with Gnielinski and Dittus-Boelter equations

III. Results and Discussions

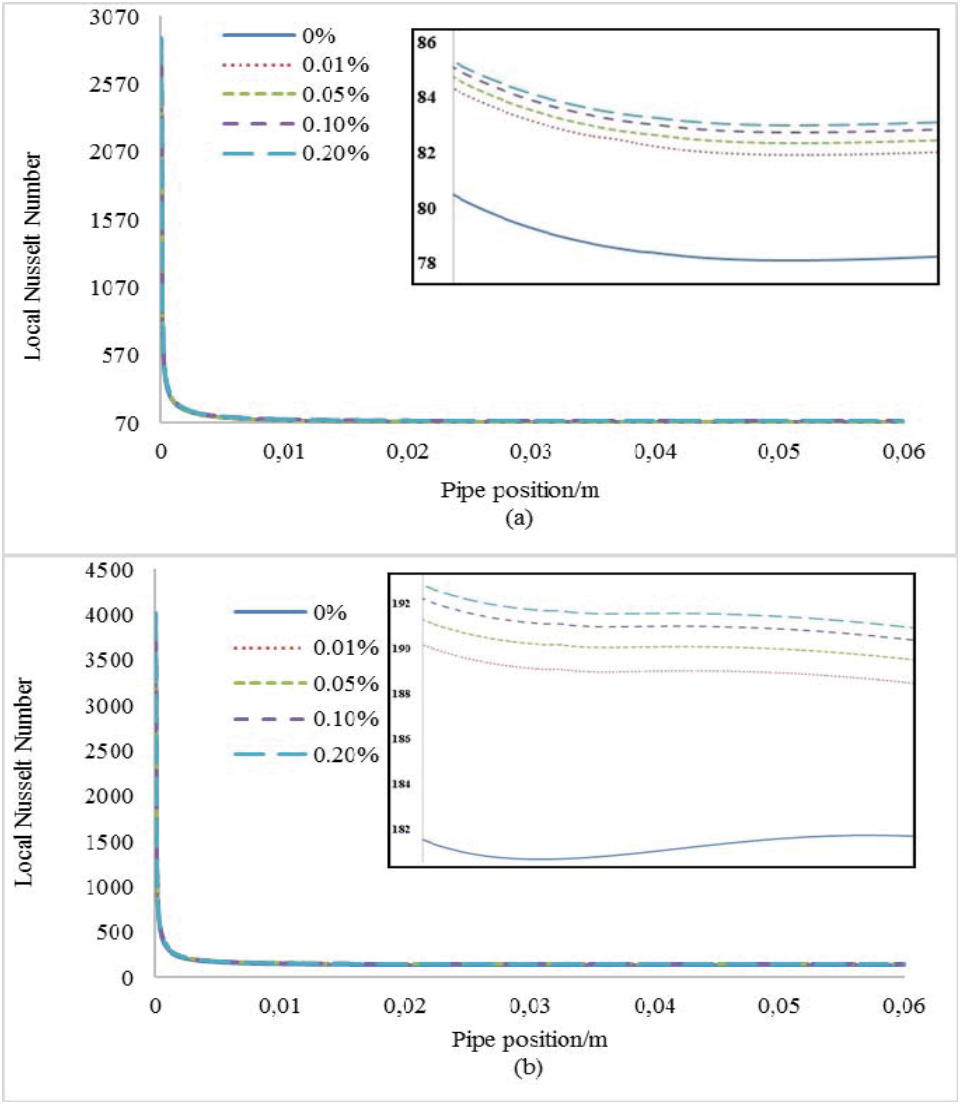
Variations of the convective heat transfer coefficient and Nusselt number of EGNP dispersed in a mixture of DI water–EG are studied, and the results are presented in this section.

Fig. 4 shows the local Nusselt number at the inner wall at the constant heat flux (q″), different mass concentrations (ϕ), and various inlet velocities (u). The curves for all simulations show an initial decrease in the local Nusselt number. After placing at the minimum position, the local Nusselt number remain constant in the axial direction due to the fully developed turbulent flow. It is shown that the EGNP loading in the base-fluid improves the thermal conductivity of fluid, increase the wall temperature as compared to the conventional base-fluid. The lower temperature difference between bulk fluid and wall tube, the higher convective heat transfer coefficient is.

Fig. 5 shows the heat transfer coefficient plots of EGNP-WEG for five different Reynolds numbers and mass

concentrations. It is realized that the enhancement of heat transfer coefficient of EGNP-WEG remarkably exceed those of the thermal conductivity improvements for different mass concentrations. The maximum heat transfer coefficient at concentration of 0.2% and Reynolds number of 17,000 is 64%. According to [50], [51], applying a simple analogy that the connective heat transfer is proportional to k/δt, where δt is the boundary thickness of thermal boundary layer. Therefore, increasing k and/or decreasing δt lead to an increase in the heat transfer coefficient. Noticeably, as reported by [51], [52], carbon nanomaterials such as graphene and CNTs decrease thickness of thermal boundary layer. As a result, heat transfer coefficient improves significantly compared to that of thermal conductivity.

Fig. 6 shows the average Nusselt numbers of EGNP-WEG for various mass concentrations and Reynolds numbers. To evaluate the ratio between convective and conductive heat transfer of EGNP-WEG coolants, Nusselt number plots have been employed. The results suggest that the Nusselt number increases remarkably in the presence of treated samples in comparison to the applied base-fluid. The EGNP loading in base-fluid improves the thermal conductivity of base-fluid, which leads to the lower temperature difference between the bulk fluid and wall tube, indicating higher Nusselt numbers and subsequently heat transfer rate.



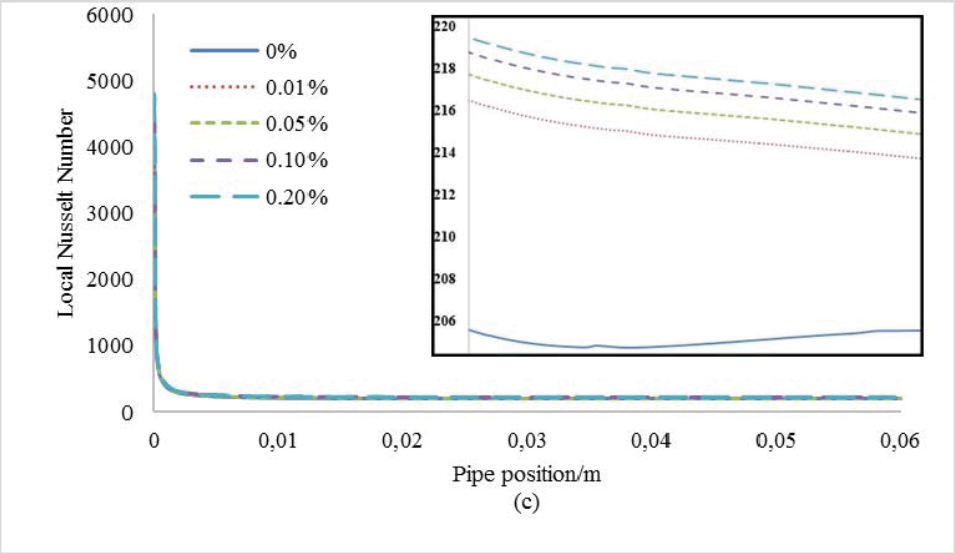


Fig. 4 Variation of the local Nusselt number for different weight concentrations and Re=5000 (a), Re=10000 (b), Re=15000 (c)

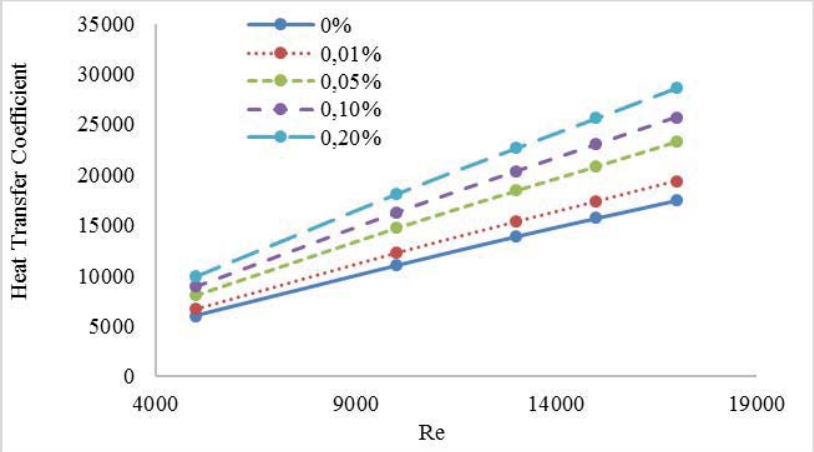


Fig. 5 Average heat transfer coefficients for various Reynolds numbers and weight concentrations

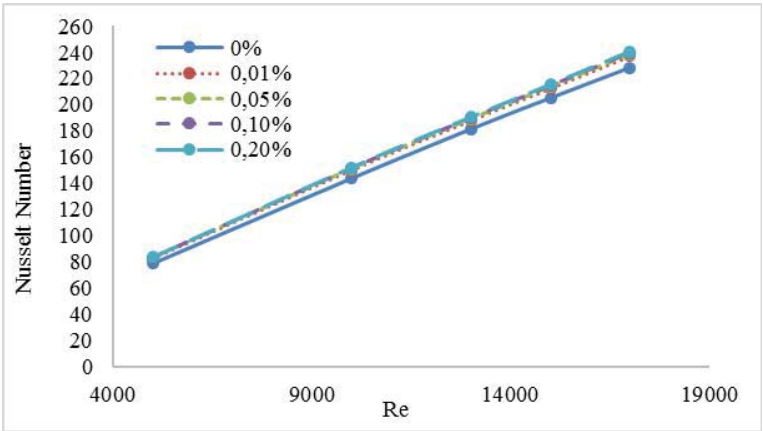


Fig. 6 Average Nusselt numbers for various Reynolds numbers and weight concentrations

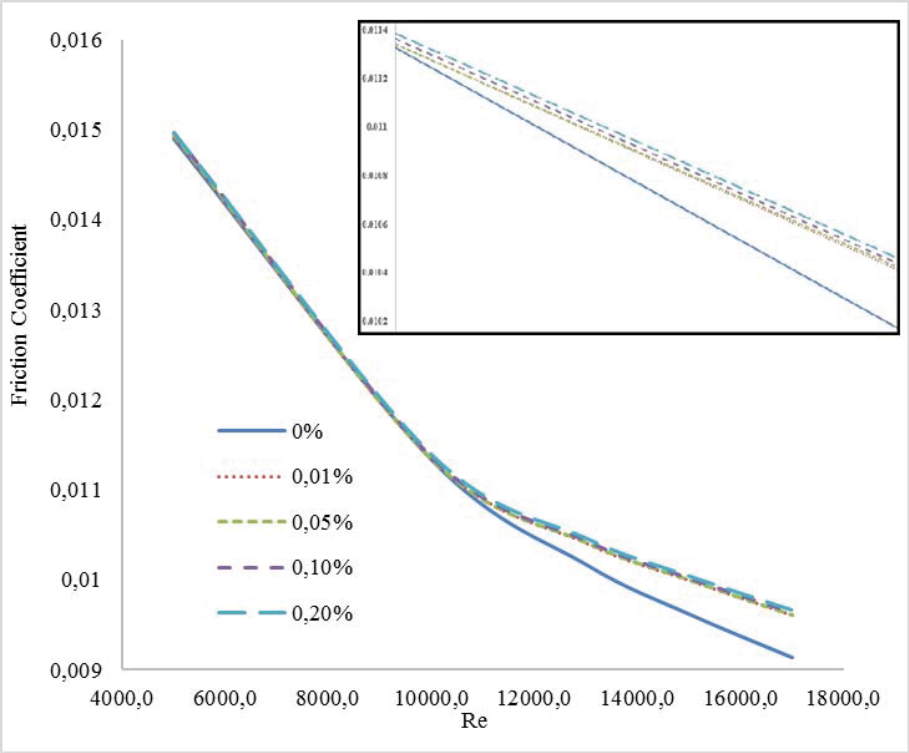


Fig. 7 Friction factor at various Reynolds numbers

Fig. 7 represents the friction factor for EGNP-WEG coolants in the annular tube at various mass concentrations and Reynolds numbers. Consistent with the present results, the friction factor increases as the concentration of EG-treated GNP increases. In addition, the friction factor decreases with increasing the flow velocity, which is a common phenomenon. The minimum value of the friction factor occurs for the base-fluid.

IV. Conclusion

Using EG-treated GNP in EGNP-WEG, without acid treatment phase, a new type of coolant with promising thermophysical properties for use in cooling applications was developed.

Thermal and flow behaviors of the prepared nanofluids throughout a horizontal annular tube have been simulated. Turbulent forced convection heat transfer with a constant heat flux has been investigated. It is indicated that this new kind of working fluid can be an effective coolant for annular heat exchangers in terms of overall thermal properties and energy saving.

The following obtained results:

- The convective heat transfer coefficient as well as Nusselt numbers of EGNP-WEG showed the significant enhancements.
- Other characteristics of the new coolant such as weak increase in the pressure drop for different concentrations, low friction factor, and appropriate performance index are of all highly favorable characteristics for introducing new fluid for wide industrial applications such as utilization in annular heat exchangers.

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References

[1] Mohammed, H.A., *Laminar mixed convection heat transfer in a vertical circular tube under buoyancy-assisted and opposed flows.* Energy Conversion and Management, 2008. 49(8): p. 2006-2015.

[2] Abu-Nada, E. and H.F. Oztop, *Effects of inclination angle on natural convection in enclosures filled with Cu–water nanofluid.* International Journal of Heat and Fluid Flow, 2009. 30(4): p. 669-678.

[3] Duka, B., et al., *Non-linear approximations for natural convection in a horizontal annulus.* International Journal of Non-Linear Mechanics, 2007. 42(9): p. 1055-1061.

[4] Passerini, A., C. Ferrario, and G. Thäter, *Natural convection in horizontal annuli: a lower bound for the energy.* Journal of Engineering Mathematics, 2008. 62(3): p. 247-259.

[5] Kashani, A., D. Jalali-vahid, and S. Hossainpour, *Numerical study of laminar forced convection of water/Al2O3 nanofluid in an annulus with constant wall temperature.* IIUM Engineering Journal, 2013. 14(1).

[6] Amiri, A., et al., *Microwave-assisted direct coupling of graphene nanoplatelets with poly ethylene glycol and 4-phenylazophenol molecules for preparing stable-colloidal system.* Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2015. 487: p. 131-141.

[7] Shanbedi, M., et al., *Optimization of the thermal efficiency of a two-phase closed thermosyphon using active learning on the human algorithm interaction.* Numerical Heat Transfer, Part A: Applications, 2014. 66(8): p. 947-962.

[8] Solangi, K., et al., *A comprehensive review of thermo-physical properties and convective heat transfer to nanofluids.* Energy, 2015. 89: p. 1065-1086.

[9] Toghraie, D., V.A. Chaharsoghi, and M. Afrand, *Measurement of thermal conductivity of ZnO–TiO2/EG hybrid nanofluid.* J Therm Anal Calorim, 2016: p. 1-9.

[10] Arzani, H.K., et al., *Toward improved heat transfer performance of annular heat exchangers with water/ethylene glycol-based nanofluids containing graphene nanoplatelets.* Journal of Thermal Analysis and Calorimetry: p. 1-10.

[11] Amiri, A., et al., *Backward-facing step heat transfer of the turbulent regime for functionalized graphene nanoplatelets based water–ethylene glycol nanofluids.* International Journal of Heat and Mass Transfer, 2016. 97: p. 538-546.

[12] Amiri, A., et al., *Laminar convective heat transfer of hexylamine-treated MWCNTs-based turbine oil nanofluid.* Energy Conversion and Management, 2015. 105: p. 355-367.

[13] Arzani, H.K., et al., *Experimental and numerical investigation of thermophysical properties, heat transfer and pressure drop of covalent and noncovalent functionalized graphene nanoplatelet-based water nanofluids in an annular heat exchanger.* International Communications in Heat and Mass Transfer, 2015. 68: p. 267-275.

[14] Arzani, H.K., et al., *Experimental investigation of thermophysical properties and heat transfer rate of covalently functionalized MWCNT in an annular heat exchanger.* International Communications in Heat and Mass Transfer, 2016. 75: p. 67-77.

[15] S. Zeinali Heris, M.N.E., S.Gh. Etemad, *Experimental investigation of convective heat transferof Al2O3/water nanofluid in circular tube.* International Journal of Heat and Fluid Flow, 2007. 28: p. 203-210.

[16] Heris, S.Z., S.G. Etemad, and M.N. Esfahany, *Experimental investigation of oxide nanofluids laminar flow convective heat transfer.* International Communications in Heat and Mass Transfer, 2006. 33(4): p. 529-535.

[17] Shanbedi, M., et al., *Thermal performance prediction of two-phase closed thermosyphon using adaptive neuro-fuzzy inference system.* Heat Transfer Engineering, 2015. 36(3): p. 315-324.

[18] Shanbedi, M., et al., *Prediction of temperature performance of a two-phase closed thermosyphon using Artificial Neural Network.* Heat and Mass Transfer, 2013. 49(1): p. 65-73.

[19] Esfe, M.H. and S. Saedodin, *Turbulent forced convection heat transfer and thermophysical properties of Mgo–water nanofluid with consideration of different nanoparticles diameter, an empirical study.* J Therm Anal Calorim, 2015. 119(2): p. 1205-1213.

[20] Beheshti, A., M. Shanbedi, and S.Z. Heris, *Heat transfer and rheological properties of transformer oil-oxidized MWCNT nanofluid.* Journal of Thermal Analysis and Calorimetry, 2014. 118(3): p. 1451-1460.

[21] Bahiraei, M., *A numerical study of heat transfer characteristics of CuO–water nanofluid by Euler–Lagrange approach.* J Therm Anal Calorim, 2016. 123(2): p. 1591-1599.

[22] Kumar, B.R., et al., *Thermal-lens probing of the enhanced thermal diffusivity of gold nanofluid-ethylene glycol mixture.* J Therm Anal Calorim, 2015. 119(1): p. 453-460.

[23] Ahammed, N., L.G. Asirvatham, and S. Wongwises, *Effect of volume concentration and temperature on viscosity and surface tension of graphene–water nanofluid for heat transfer applications.* J Therm Anal Calorim, 2016. 123(2): p. 1399-1409.

[24] Hosseinzadeh, M., et al., *Convective heat transfer and friction factor of aqueous Fe3O4 nanofluid flow under laminar regime.* J Therm Anal Calorim: p. 1-12.

[25] Esfe, M.H., et al., *Designing artificial neural network on thermal conductivity of Al2O3–water–EG (60–40%) nanofluid using experimental data.* Journal of Thermal Analysis and Calorimetry: p. 1-7.

[26] Arzani, H.K., et al., *Heat transfer performance of water-based tetrahydrofurfuryl polyethylene glycol-treated Graphene Nanoplatelets nanofluids.* RSC Advances, 2016.

[27] Chol, S., *Enhancing thermal conductivity of fluids with nanoparticles.* ASME-Publications-Fed, 1995. 231: p. 99-106.

[28] Barbés, B., et al., *Thermal conductivity and specific heat capacity measurements of CuO nanofluids.* Journal of Thermal Analysis and Calorimetry, 2014. 115(2): p. 1883-1891.

[29] Roy, G., C.T. Nguyen, and P.-R. Lajoie, *Numerical investigation of laminar flow and heat transfer in a radial flow cooling system with the use of nanofluids.* Superlattices and Microstructures, 2004. 35(3): p. 497-511.

[30] Khanafer, K., K. Vafai, and M. Lightstone, *Buoyancy-driven heat transfer enhancement in a two-dimensional enclosure utilizing nanofluids.* International Journal of Heat and Mass Transfer, 2003. 46(19): p. 3639-3653.

[31] Akbarinia, A. and A. Behzadmehr, *Numerical study of laminar mixed convection of a nanofluid in horizontal curved tubes.* Applied Thermal Engineering, 2007. 27(8): p. 1327-1337.

[32] Akbarinia, A. and R. Laur, *Investigating the diameter of solid particles effects on a laminar nanofluid flow in a curved tube using a two phase approach.* International Journal of Heat and Fluid Flow, 2009. 30(4): p. 706-714.

[33] Talebi, F., A.H. Mahmoudi, and M. Shahi, *Numerical study of mixed convection flows in a square lid-driven cavity utilizing nanofluid.* International Communications in Heat and Mass Transfer, 2010. 37(1): p. 79-90.

[34] Shahi, M., A.H. Mahmoudi, and F. Talebi, *Numerical study of mixed convective cooling in a square cavity ventilated and partially heated from the below utilizing nanofluid.* International Communications in Heat and Mass Transfer, 2010. 37(2): p. 201-213.

[35] Sundar, L.S. and K. Sharma, *Turbulent heat transfer and friction factor of Al 2 O 3 nanofluid in circular tube with twisted tape inserts.* International Journal of Heat and Mass Transfer, 2010. 53(7): p. 1409-1416.

[36] Arzani, H.K., et al., *Numerical Study of Developing Laminar Forced Convection Flow of Water/CuO Nanofluid in a Circular Tube with a 180 Degrees Curve.*

[37] Amiri, A., et al., *Toward improved engine performance with crumpled nitrogen-doped graphene based water–ethylene glycol coolant.* Chemical Engineering Journal, 2016. 289: p. 583-595.

[38] Manninen, M., V. Taivassalo, and S. Kallio, *On the mixture model for multiphase flow*. 1996, Technical Research Centre of Finland Finland.

[39] Crowe, L.M., D.S. Reid, and J.H. Crowe, *Is trehalose special for preserving dry biomaterials?* Biophysical journal, 1996. 71(4): p. 2087.

[40] Ishii, M., *Thermo-fluid dynamic theory of two-phase flow.* NASA STI/Recon Technical Report A, 1975. 75: p. 29657.

[41] Xu, H.-K., *Viscosity approximation methods for nonexpansive mappings.* Journal of Mathematical Analysis and Applications, 2004. 298(1): p. 279-291.

[42] Arzani, H.K., et al., *Thermophysical and Heat Transfer Performance of Covalent and Noncovalent Functionalized Graphene Nanoplatelet-Based Water Nanofluids in an Annular Heat Exchanger.* World Academy of Science, Engineering and Technology, International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering. 10(2): p. 180-187.

[43] Lotfi, R., Y. Saboohi, and A. Rashidi, *Numerical study of forced convective heat transfer of nanofluids: comparison of different approaches.* International Communications in Heat and Mass Transfer, 2010. 37(1): p. 74-78.

[44] Bianco, V., et al., *Numerical investigation of nanofluids forced convection in circular tubes.* Applied Thermal Engineering, 2009. 29(17): p. 3632-3642.

[45] Mirmasoumi, S. and A. Behzadmehr, *Effect of nanoparticles mean diameter on mixed convection heat transfer of a nanofluid in a horizontal tube.* International journal of heat and fluid flow, 2008. 29(2): p. 557-566.

[46] Mirmasoumi, S. and A. Behzadmehr, *Numerical study of laminar mixed convection of a nanofluid in a horizontal tube using two-phase mixture model.* Applied Thermal Engineering, 2008. 28(7): p. 717-727.

[47] Behzadmehr, A., M. Saffar-Avval, and N. Galanis, *Prediction of turbulent forced convection of a nanofluid in a tube with uniform heat flux using a two phase approach.* International Journal of Heat and Fluid Flow, 2007. 28(2): p. 211-219.

[48] Shih, T.M., *Numerical heat transfer*. 1984: CRC Press.

[49] Launder, B.E. and D. Spalding, *The numerical computation of turbulent flows.* Computer methods in applied mechanics and engineering, 1974. 3(2): p. 269-289.

[50] Aravind, S.J., et al., *Investigation of structural stability, dispersion, viscosity, and conductive heat transfer properties of functionalized carbon nanotube based nanofluids.* The Journal of Physical Chemistry C, 2011. 115(34): p. 16737-16744.

[51] Aravind, S.J. and S. Ramaprabhu, *Graphene–multiwalled carbon nanotube-based nanofluids for improved heat dissipation.* RSC Advances, 2013. 3(13): p. 4199-4206.

[52] Ding, Y., et al., *Heat transfer of aqueous suspensions of carbon nanotubes (CNT nanofluids).* International Journal of Heat and Mass Transfer, 2006. 49(1): p. 240-250.