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NUMERICAL MODELING OF LAMINAR FORCED CONVECTIVE ENHANCEMENT OF (AL_2O_3-WATER) NANOFLUIDS IN A CIRCULAR PIPE

Salah M. Salih[1] and Duna Tariq Yaseen[2]

[1] Lecturer, Department of Power Mechanical Technical Engineering, Engineering Technical College of Al-Najaf, Al-Furat Al-Awsat Technical University, Al-Najaf, Iraq. Email: salahmahditech@yahoo.com

[2]Asst. Lecturer, Power Mechanic Techniques Department, Basrah Technical Institute, South Technical University, Al- Basrah, Iraq. Email: duna.yaseen@stu.edu.iq

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ABSTRACT

A two-dimensional numerical investigation on laminar forced convection is carried out to estimate the thermal and fluid field behavior of Al_2O_3-water nanofluid in a circular pipe with constant heat flux. In this study, the finite element method (FEM) is employed to analyze the continuity, momentum, and energy governing equations by using COMSOL Multiphysics 3.5a. Computations of heat transfer rates were performed for a range of Reynolds numbers ($Re \leq 2000$), and ($Pr= 5.42$). The effects of Reynolds number and fraction volume of nanoparticle ($\phi \leq 5\%$) on the mean coefficient of convection (havg), pressure drop (ΔP), and thermal-hydraulic performance are investigated. The computations indicate that Al_2O_3 nanoparticle usage augments the average coefficient of heat convection significantly, and which is increased by (10%) with maximum pressure loss (15%) for (ϕ=5%) and high Reynolds number when compared to the base fluid. The present model is validated with empirical Shah Equation and the results showed a good agreement.

KEYWORDS: Forced Convective Enhancement, Nanofluid Flow, Circular Pipe.

1. INTRODUCTION

In recent research, the augmenting advances in industrial technology. The term 'nanofluid' is created by dispersing nanometer-sized particles that are suspended in conventional heat flow basic fluids like; water, oil, ethylene glycol (EG), propylene have led to the production of the nanoparticles. Mixing of these nanomaterials in a pure fluid makes a superior class of fluids, called 'nanofluids'glycol. By using nanoparticles metallic with high conductivity in scales of (1–100) nm such as: (Cu, Ag, Al_2O_3, CuO, and TiO_2). To enhance the effective conductive of the mixture that leads to augment their overall convection interchange, (Xuan and Li 2003, Bianco, Manca, et al. 2014). Nanofluids which provide effectiveness as an advanced methodology of thermal-fluid application in the heating of the building, energy exchanger plants, and lubricant cooling of the automobile, through the high effective thermal conductivity. Consequently, many researchers worked on improving the thermal- physical properties of conventional operating fluids by utilizing nanoparticles to make nanofluids and provide desired energy exchange. Many studies indicate the behaviors forced convective heat and nanofluids flow in the same operating conditions. The influence of Re number and nanomaterials fraction volume of (Al_2O_3, and TiO_2) which was suspended with water as a nanofluid on Nu number was investigated by (Pak and Cho 1998). The results show that Nu number augmented by increasing Re number and volume fraction of nanoparticles. Heyhat et al. (Heyhat, Kowsary, et al. 2013) studied experimentally the characteristics of thermal transfer by laminar convection and pressure drop of Al_2O_3- nanofluid water at a constant temperature of the wall. It can be noticed that the coefficient of heat convection of the nanofluid was greater than the pure fluid and heat improvement of the augmented transfer with an increase in Re Number and concentration of particles.

(Koo and Kleinstreuer 2005) investigated the steady laminar flow of CuO-nanomaterial suspended with a base fluid like water or ethylene-glycol in micro-heatsinks and located that a high Prandtl range base fluid and a high ratio channel provide higher heat transfer performance. Numerical modeling of forced convection enhancement by utilizing various nanofluids flow in a two-dimensional horizontal channel with isothermally heated walls with two fins was analyzed by Salah M. Salih, (Salih 2013). Computations found the increment in average Nu number is strongly dependent on the nanoparticle is chosen and boundary condition of used fins. Also, the results showed that the heat convection augmentation for pure water and nanofluid at concentration (5%) Al_2O_3-H_2O is (1.15, and 1.36) respectively. A numerical investigation of a laminar forced convective nanofluids flow in the heat exchanger device is analyzed by Maiga et al. (Maiga, Palm et al. 2005). Two geometrical models have been used to analyze the thermal behavior of the nanofluid in a specifically uniformly heated tube and a system of parallel, concentrically and heated disks. Results show that Reynolds variety and also the gap between disks have an insignificant impact on the coefficient of heat convection improvement.

(Wen and Ding 2004) studied laminar forced convection of Al_2O_3-water nanofluids flow in a tube. Results presented that improvement of heat flow was augmented as any increase of the concentration of nanoparticle at a fixed Re number. Later, the forced convective flow of (CuO, and Al_2O_3)-water as nanofluids in a circular pipe under an isothermal temperature of wall condition has been investigated experimentally and numerically by (Heris, et al. 2006, Heris, Esfahany et al. 2007). Their tests additionally exhibited that increased concentration of nanoparticle augmented the enhancement of the heat convection coefficient. (Ho, Chang et al. 2018) tested and analyzed the influence of (Al_2O_3-water) nanofluid on the forced convection behaviour in the tube. They found that the augmentation Nu number, while it also leads to a higher in the pressure drop along the tube walls using nanoparticles. The study of the nanofluid characteristics of forced convective in a circular pipe were numerically analyzed by (Berberović and Bikić 2019). The results showed that the enhancement of heat convection is better for ethylene glycol-based silicon nitride as compared to the pure fluid at the same flow rate.

In the current analysis, a two-dimensional numerical investigation for steady-state laminar forced convection is carried out to evaluate flow and heat transfer characteristics of Al_2O_3-water nanofluid in a circular pipe under a constant heat flux. To analyze the influence of Re number, and the fraction volume of nanofluid on the heat convective augmentation and pressure drop inside a circular pipe.

2. MODEL FORMULATION

The numerical investigation is performed nanofluid flowing in a circular pipe having a diameter of (0.05 m) and a length of (5 m). The flow enters the pipe with a uniform cold temperature and a uniform axial velocity. To analyze and construct the governing equations with (water- Al_2O_3) as nanofluid was simplified under the following assumptions:

1. A two-dimensional, a steady state, an incompressible and a laminar forced convection flow in the pipe.

2. A nanofluid is assumed to be and Newtonian fluid.
3. The thermophysical properties of nanofluid are considered constant except for density variation which is dependent on Boussinesq approximation.
4. A viscous dissipation and body forces are neglected.

Hence, the governing equations are given as follows:

Continuity equation:

$$\nabla.\rho_{nf}\vec{V}=0 \tag{1}$$

Momentum equation:

$$\nabla.(\rho_{nf}\vec{V}\vec{V})=-\nabla P+\nabla.(\mu_{nf}\nabla^{2}\vec{V}) \tag{2}$$

Energy equation:

$$\nabla.(\rho_{nf}\vec{V}Cp_{nf}T)=\nabla.(K_{nf}\nabla T) \tag{3}$$

The thermal-fluid boundary conditions are applied in Eqs. (1 to 3), are a uniform inlet velocity Uin, no-slip flow at the pipe surfaces, and outlet pressure equals to zero. In addition, the boundary conditions of thermal are a uniform inlet temperature Tin, and the pipe walls were subjected to a uniform heat flux of (3000 W/m2). As shown in Fig. 1. At the exit section, the thermal-fluid fields were assumed to be fully developed (X/D > 100). The thermophysical properties of the basic fluids and the nanoparticle are presented in Table 1. The nanofluid properties are expressed as, (Oztop and Abu-Nada 2008, Salah Mahdi Salih 2017):

$$\rho_{nf}=(1-\phi)\rho_{f}+\phi\rho_{s} \tag{4}$$

$$(\rho c)_{nf}=(1-\phi)(\rho_{f}c_{f})+\phi(\rho_{s}c_{s}) \tag{5}$$

The effective thermal conductivity of the nanofluid is approximated by the Maxwell–Garnetts model, (Oztop and Abu-Nada 2008) :

$$k_{eff}=\frac{k_{nf}}{k_{f}}=\frac{k_{s}+2k_{f}-2\phi(k_{f}-k_{s})}{k_{s}+2k_{f}+\phi(k_{f}-k_{s})} \tag{6}$$

Moreover, the effective dynamic viscosity of the nanofluid which is given by (Brinkman 1952):

$$\mu_{nf} = \frac{\mu_f}{(1-\phi)^{2.5}} \tag{7}$$

Table 1: Thermo-physical of nanofluid properties, (Oztop and Abu-Nada 2008, Salah Mahdi Salih 2017).

Physical property	Base fluid	Nanoparticle
	water	Al_2O_3
(kg/m^3) ρ	997.1	3970
Cp **(J/kg.K)**	4179	765
k **(W/m.K)**	0.613	40

$$Nu_x = \frac{h_x D}{k_f} \tag{8}$$

where (D) is a pipe diameter and (h_x) coefficient of local heat transfer is obtained as:

$$h_x = \frac{q_x}{T_w - T_b} \tag{9}$$

The average of heat transfer coefficient is expressed as:

$$h_{avg} = \frac{1}{L}\int_0^L h_x dx \tag{10}$$

The performance of the thermal-hydraulic factor is obtained by, (Mashaei, Hosseinalipour et al. 2012):

$$\eta = \frac{(h_{avg})_r}{(\Delta P)_r^{1/3}} \tag{11}$$

Where, $(h_{avg})_r$ and $(\Delta P)_r$ are the coefficient of mean heat convection and the ratio of pressure drop, respectively according to obtained values of base fluid.

3. NUMERICAL PROCEDURES

Present studied, a COMSOL Multiphysics 3.5a was employed to analyze the governing Eq. 1-3 to predict the velocity, pressure, and temperature fields. Using (FEM) scheme for converting the governing equations into algebraic equations. The computational domain was occupied three different amount of mesh elements: (2432, 6464, and 9728) were implemented and compared in terms of velocities, and pressure in the centerline of pipe to ensure a mesh independent solution.

In this study, the mesh of (6464) elements is taken to be a good satisfied to ensure the precision of numerical results with maximum error (3.29 %), as shown in Figs. 2 and 3. The validation of the computational model was successfully validated the local Nusselt number obtained from present computations data with the empirical Shah equation data (Shah, London et al. 1980, Kakaç, Shah et al. 1987) for pure water under a constant heat flux of the circular pipe at (Re=1000), and the results showed a good agreement, as presented in Fig. 4.

$$Nu_x = \begin{cases} 1.077 X_*^{-1/3} - 0.70 , & X_* \le 0.01 \\ 3.657 + 6.874 (10^3 X_*)^{-0.488} e^{-57.2 X_*}, & X_* \ge 0.01 \end{cases} \tag{12}$$

Where, $Nu_x = h_x D / k_f$, $X_* = [(x/D)/(\mathrm{Re}\,\mathrm{Pr})]$

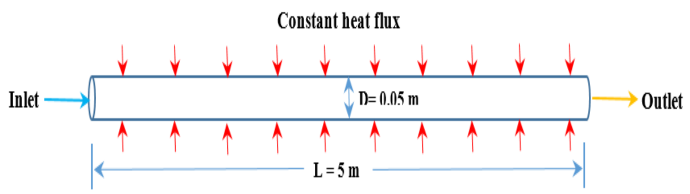

Fig. 1. Schematic of geometry problem.

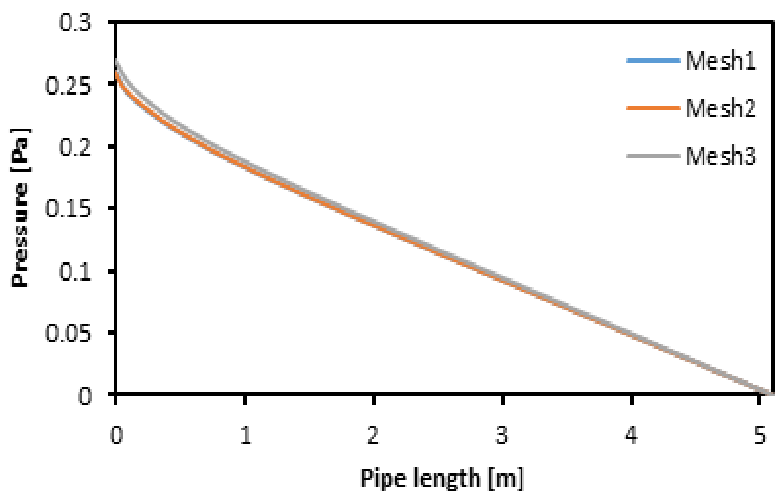

Fig. 2. Pressure variation along the pipe length for different mesh elements.

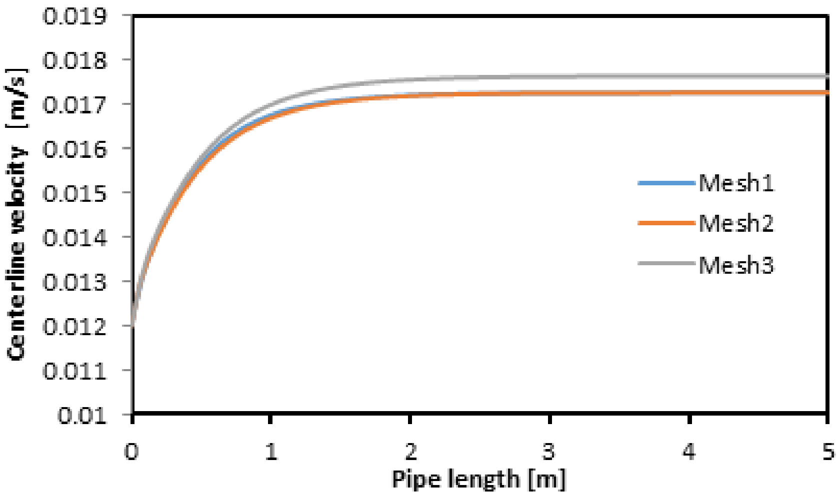

Fig. 3. Centerline velocity variation along the pipe length for different mesh elements.

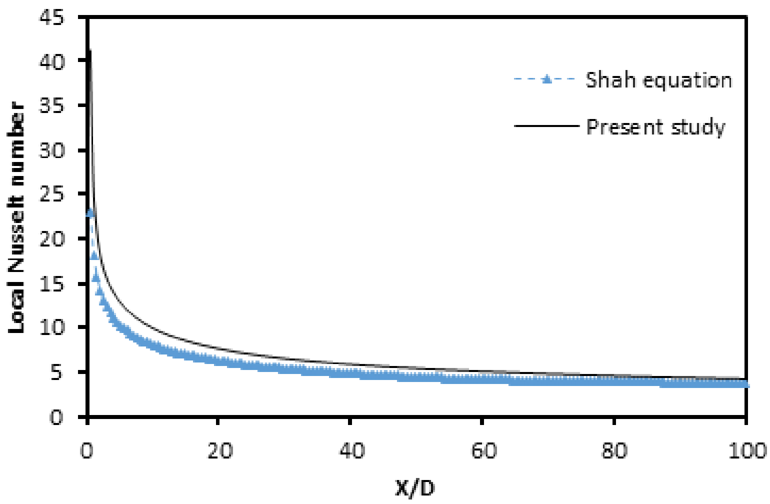

Fig. 4. Validation between the numerical data and the empirical Shah equation for water under constant heat flux at (Re=1000).

4. RESULTS AND DISCUSSION

The computational results expose that the existence of nanofluid has a significant influence on the heat convection augmentation. The coefficient of mean heat convection profile versus Reynolds number (Re) is represented in Fig. 5 for (ϕ=0, 3, and 5 %). Generally, the coefficient of mean heat convection increases as (Re) is increased. Also, it is detected that the average heat transfer coefficient becomes higher by increasing the fraction volume of nanomaterial (ϕ) at a constant value of Re number.

Fig. 6 shows the mean heat convection coefficient ratio versus Re number for (ϕ=3 and 5 %). It can be noticed the (havg) ratio is higher than one for all studied cases and approximately remains constant as Re number increases from (500 to 2000) for fractions volume (ϕ=3 and 5 %). Moreover, there is a significant increase in lower fraction volume in comparison with a higher one. Really, the maximum value of (1.09) is perceived at (Re=2000 and ϕ=5 %). The heat transfer enhancement is achieved at the cost of pressure loss. In Fig. 7 the effects of (Re and ϕ) on the pressure drop of Al_2O_3/water nanofluid at (ϕ=0 (pure water), 3 and 5 %) are presented. Obviously, increasing of Re number and particle volume fraction due to an increase in the pressure drop and the maximum value about (0.97 Pa) are detected at (Re=2000 and ϕ=5 %). The ratio of pressure drop represented to the pure fluid is seen in Fig. 8. It is detected that (ΔP) ratio is larger than one for all confirmed tests, similar to (havg) ratio, and there is no significant change as Re number increases from (250 to 2000).

Furthermore, employing nanofluid improves the heat exchange rate besides pressure drop. To analyze the improvement of thermal convection and pressure loss for different Re numbers and volume fractions, the thermal-hydraulic performance factor (η) as a function of Re number is shown in Fig. 9 for (ϕ=3 and 5 %). Also, it can be noticed the increase of Re number and fraction volume of nanoparticle led to the increment of thermal- hydraulic performance factor (η) and the maximum value about (1.045) is detected at (Re=2000 and ϕ=5 %). It is noted that the use of nanofluid in the cooling of the pipe wall has a better thermal performance.

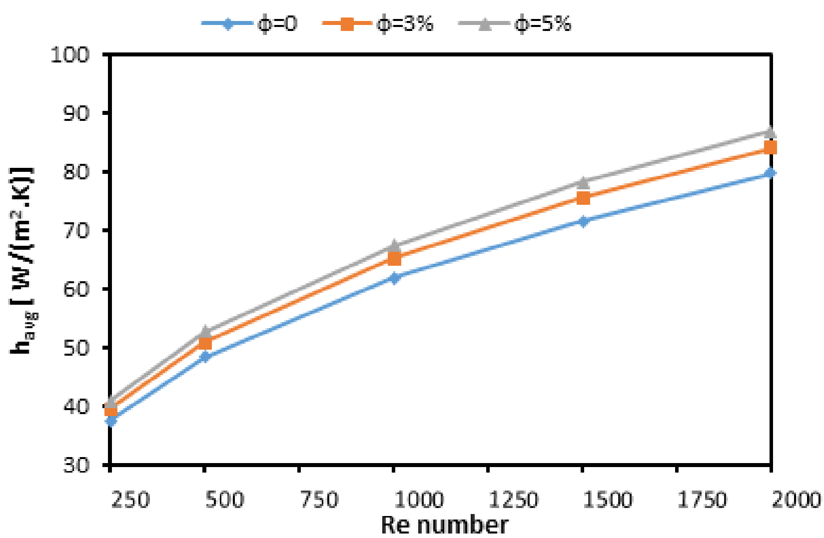

Fig. 5. Coefficient of mean heat convection versus Re number for various (ϕ).

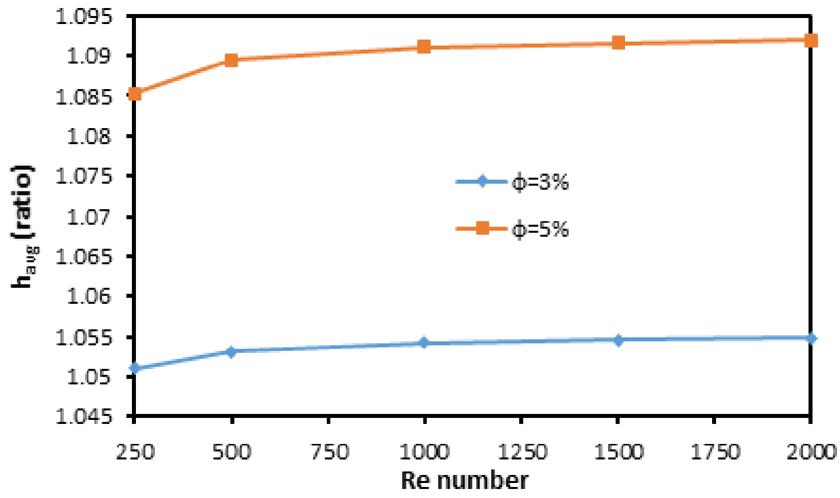

Fig. 6. Coefficient of mean heat convection ratio versus Re number for various (ϕ).

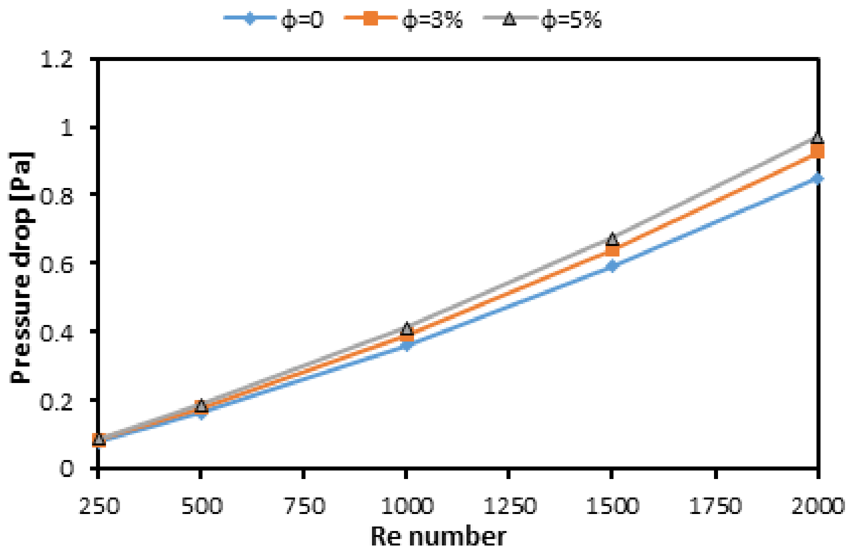

Fig. 7. Pressure drop versus Re number for various (ϕ).

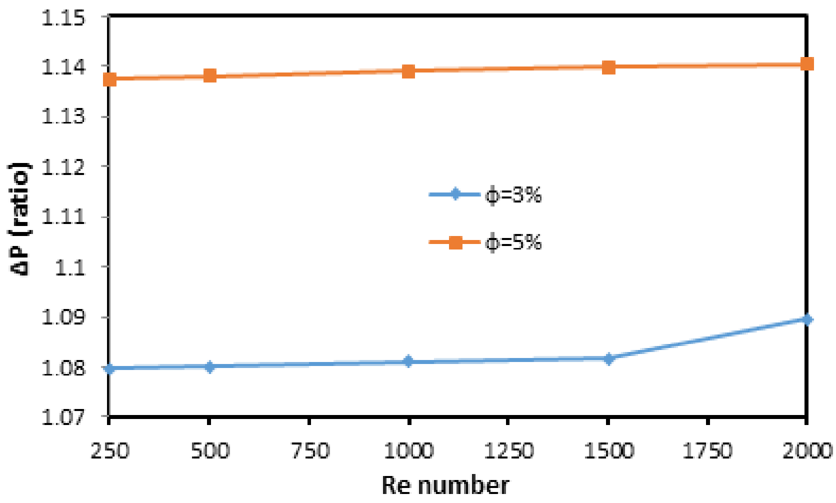

Fig. 8. Pressure drop ratio versus Re number for various (ϕ).

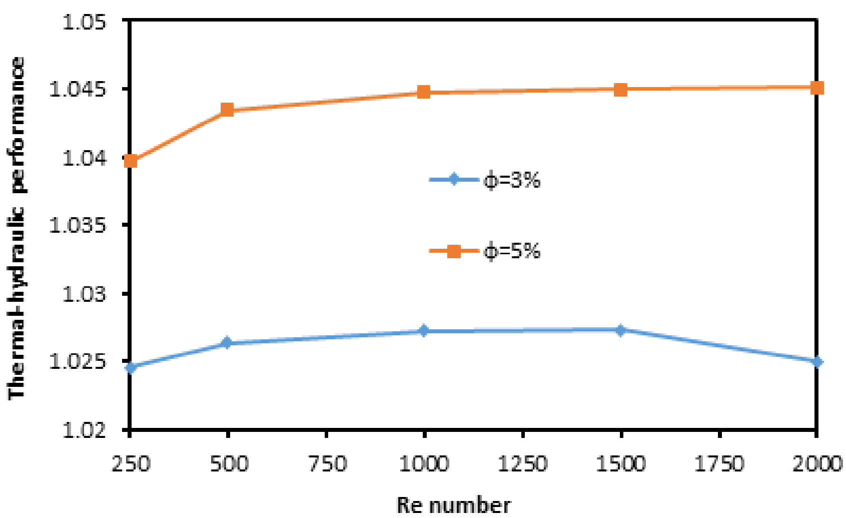

Fig. 9. Thermal-hydraulic performance (η) versus Re number for various (ϕ).

5. CONCLUSION

Main important conclusions of current work can be summarized as follows:

1. Computational results demonstrated that the maximum average heat transfer coefficient enhancement occurs at (Re=2000 and ϕ=5 %) of Al_2O_3-water nanofluid.
2. The usage Al_2O_3 nanoparticle augments the mean heat convection coefficient significantly.
3. A maximum value of averaged heat convection coefficient increment about (10%), and increase in pressure drop about (15%) for (ϕ=5%) and high Reynolds number when compared to the base fluid.

4. The incremental change in the average heat transfer coefficient is strongly dependent on (Re) number, volume fraction (ϕ).
5. Finally, the presence of nanoparticles in the base fluid can typically improve the heat convection rate and very important for the convective heat transfer heating application.

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