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Aluminum Oxide Nanofluid Energy Transfer

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Abstract

Nanofluid is a new class of heat transfer fluids engineered by dispersing metallic or non-metallic nanoparticles with a typical size of less than 100 nm in the conventional heat transfer fluids.This article aims to investigate the overall and convection heat transfer coefficient and Nusselt number of Al_2O_3-water nanofluid flowing in a horizontal double pipe heat exchanger under turbulent flow ($14000 \leq Re \leq 26500$) conditions. Al_2O_3 nanoparticles with diameter of 20 nm dispersed in Deionized water with volume concentrations of $0.1\% \leq \varphi \leq 0.3\%$ vol. are used as the test fluid. The results show that the overall and convection heat transfer coefficient and Nusselt number of nanofluid were approximately 15% -21% greater than that of pure fluid. Additionally, the heat transfer coefficient and Nusselt number increase with an increase in flow rate,Reynolds number, nanoparticle concentration and nanofluid temperature. Finally, the new correlations were proposed for predicting the Nusselt number of the nanofluids, especially. Employing particles of nanometer dimension suspended in solution as nanofluid shows considerable increase in the nanofluid thermal conductivity and heat transfer coefficient which result in increasing heat transfer and decreasing operational cost.

1. Introduction

With respect to utilizing nanoparticles in many processes, attention has been focused on the improvement of heat exchanger efficiency by adding solid particles to heat transfer fluids. Many researches have investigated the effect of nanoparticles on different process parameters like hydrodynamic and thermo-physical properties. However, seldom researches were performed to evaluate the effect of turbulent nanofluid flow on heat transfer. Nanofluid, a suspension of particles of nanometer-size in conventional liquids like water, oil or ethylene glycol, has shown a number of potential advantages in thermal applications. In addition, some of the oxide particles show a good dispersing in conventional heat transfer fluids.

Aghayari et al. [1] reported experimental results which illustrated the dispersion of the heat transfer and Overall heat transfer coefficient of AL_2O_3 nanoparticles in liquid for turbulent flow in a double pipe heat exchanger. Impacts of the Reynolds number, volume fraction, temperature and nanoparticle source on the Overall heat transfer coefficient have been investigated.

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Nomenclature

		Greek Symbols	
A	heat transfer area (m^2)	ΔT_{lm}	logarithmic mean temperature difference(^{o}C)
Cp	specific heat (kJ kg^{-1} ^{o}C^{-1})	ΔP_{nf}	pressure drop
D	tube diameter (m)	α	thermal diffusivity (m^2/s)
d	nanoparticle diameter (m)	ρ	density (kg m^{-3})
h	convective heat transfer coefficient (W m^{-2o}C^{-1})	ϑ	Kinematic viscosity (m^2/s)
k	thermal conductivity (W m^{-1o}C^{-1})	φ_V	nanoparticle volume concentration (Dimensionless)
L	tube length (m)	**Subscripts**	
m^o	mass flow rate (kg s^{-1})	f	fluid
Nu	Nusselt number (Dimensionless)	i	inside
Pe	Peclet number (Dimensionless)	in	inlet
Pr	Prandtl number (Dimensionless)	m	mean
Q	Heat transfer rate (W)	nf	nano fluid
Re	Reynolds number (Dimensionless)	o	outside
T	temperature (^{o}C)	out	outlet
U	overall heat transfer coefficient (W m^{-2o}C^{-1})	p	particles
V	velocity (m^{2}s^{-1})	w	wall
f	friction factor		

The experimental results showed that the heat transfer coefficient increases with the Reynolds number and the particle concentration. Aluminum oxide nanofluid with concentrations of 0.2 and 0.3 had high thermal efficiency compared to the base fluid. For example, this amount is 1450000 for water at a constant mass flow rate and a temperature of 50°C. This amount is 1565000 and 1580000 for the nanofluid at the concentrations of 0.2 and 0.3, respectively. Thermal efficiency of water and nanofluid with the concentration of 0.1 is 1103842 and 1123123, respectively (in Reynolds of 23000) which is approximately 1.71% higher than the heat transfer of the base fluid. This increase can be attributed to the immigration of the particles, non-uniform distribution of the thermal conductivity and viscosity of the fluid which decreases the boundary layer thickness, resulting in the delay in the development of the thermal boundary layer. He et al[2] reported an experimentally study investigating the heat transfer performance and flow characteristic of TiO$_2$-distilled water nanofluids flowing through a vertical pipe in an upward direction under a constant heat flux boundary condition in both a laminar and a turbulent flow regime. Their results showed that at a given Reynolds number and particle size, the heat transfer coefficient raised with increasing nanoparticle concentration in both laminar and turbulent flow regimes. Similarly, heat transfer coefficient was not sensitive to nanoparticle size at a given Reynolds number and particle size. Moreover, the results indicated that the pressure drop of the nanofluids was very close to that of the base fluid. Nguyen et al. [3] investigated the heat transfer coefficient and fluid flow characteristic of Al$_2$O$_3$ nanoparticles dispersed in water flowing through a liquid cooling system. The results revealed that the nanofluid gave a higher heat transfer coefficient than the base liquid and the nanofluid with a 36 nm particle diameter gave higher heat transfer coefficient compared to the nanofluid with a 47 nm particle diameter. Wen and Ding[4] studied the convective heat transfer coefficients in which Al$_2$O$_3$ nanoparticles were suspended in deionized water for laminar flow in a copper tube under a constant wall heat flux and focused in particular on the entrance region. Alumina nanoparticles of 27–56 nm in size were used in this study. The results show that the local heat transfer coefficient varied with the Reynolds number and particle concentration. In particular, it was found that the use of nanofluids at the entrance region resulted in a pronounced increase in the heat transfer coefficient, causing a decrease in the thermal boundary layer thickness which decreased with the axial distance. This behaviour implied that it might be

possible to create a ''smart entrance'' region to meet the highest performance of nanofluids. Furthermore, the calculated Nusselt number using the Shah correlation for laminar flow and the Dittus–Boelter equation for turbulent flow did not coincide with the experimental results.

2.Experimental Setup

The experiment to investigate heat transfer characteristic of nanofluid were carried out using the experimental apparatus as shown in figure 1(a,b). The experimental apparatus consists of a double pipe heat exchanger, two circulation pumps, two flow meter, two ratameter, two receiving tanks with the capacity of 15 and 30 liter in which working fluids are stored and two flow meters.

The heat exchanger was thermally insulated by a insulation with thermal conductivity of k=0.004 w/mk in order to reduce heat loss along the axial direction. The test section includes two axially stainless steel(SS 304) pipes, inner tube with 1100mm length and 6mm inner diameter and 8 mm outer diameter, the otter tube with 1200mm length and 14mm inner diameter and 16mm outer diameter respectively. Two measure the inner tube temperature at different locations and the inlet and outlet temperature of the fluids, two data logger have been employed with 4 exit portals for each of them. One of them consists of 4 K-type thermocouples to measure the inlet and exit temperatures of hot and cold fluids which are inserted directly into the flow.

Another data logger with 4 thermocouples which of the thermocouples were taped along the inner tube wall at equally space to measure the circumferential temperature variation. The temperature and flow rates of input nanofluids were controlled by data logger, flow meter and a by-pass valve before flow in the test section installed in the output line of the circulation pump.

The pressure drops across the test section were measured by using inclined U-tube manometers The nanofluid flow rate was measured by a magnetic flow meter and which was placed at the entrance of the test section. In each test run, it was necessary to record the data of temperature and volumetric flow rate.
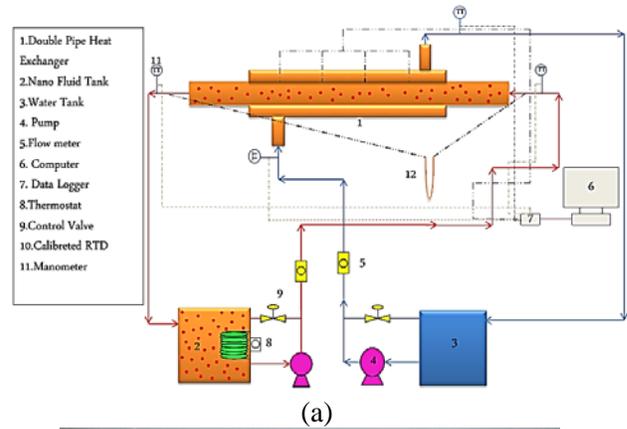

(a)

(b)

Fig. 1. Exprimental setup

3. Nanofluid preparation

The nanofluid used in the experiment was 99.0+% pure aluminum oxide pre-dispersed in Water, with an average particle size of 20 nm. The Nanofluid was mixed with de-ionized water To prepare experimental concentrations (Table 1). NF samples were then underwent mixing by ultra-sonic method between 3 to 4 hours to ensure complete dispersion is achieved. The morphology of Al_2O_3 nano-particles was studied by using TEM (Figure 2).
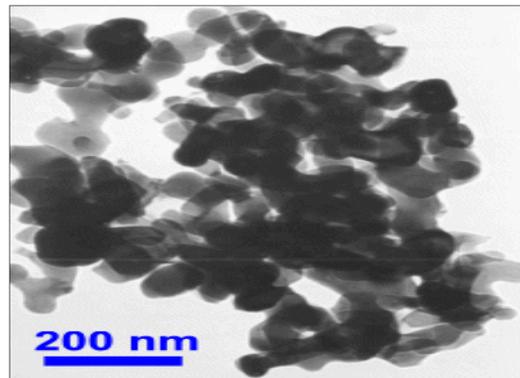

Fig. 2. The TEM image of Al_2O_3 nano-particles

3. Data processing

The experimental data were used to calculate overall heat transfer coefficient, convective heat transfer coefficient and Nusselt number of nanofluids with various particle volume concentrations. For fluid flows in a concentric tube heat exchanger, the heat transfer rate of the hot fluid (nanofluid) in the inner tube can be expressed as[5]:

$$Q_{(nf)} = \overset{\circ}{m}_{nf} C_{p\,nf}(T_{out} - T_{in})\qquad(1)$$

Where $\overset{\circ}{m}_{nf}$ is the mass flow rate of the nanofluid (hot fluid), and T_{out} and T_{in} are the outlet and inlet temperatures of the nanofluid (hot fluid), respectively. While the heat transfer of the cold fluid (water) for the outer tube is[5]:

$$Q_{bf} = \overset{\circ}{m}_{bf} C_{pbf}(T_{in} - T_{out})\qquad(2)$$

Where $\overset{\circ}{m}$ is the mass flow rate of the water (cold fluid), and T_{in} and T_{out} are the inlet and outlet temperatures of the water (cold fluid), respectively.
The average heat transfer rate between nanofluid and cooling water is calculated as follows[6]:

$$\frac{Q_{nf} + Q_{bf}}{2}\qquad(3)$$

The density and specific heat of the nanofluids are calculated by use of the Pak and Cho[7] correlations, which are defined as follows:

$$\rho_{nf} = (1 - \varphi_V)\rho_f + \varphi_v\rho_p\qquad(4)$$

Subscripts f, p and nf refer to the base fluid, the nanoparticles, and the nanofluid, respectively. φ_V is the nanoparticle volume concentration. $(C_p)_{nf}$ is the effective specific heat of the nanofluid which can be calculated from Xuan and Roetzel relation [8]:

$$(C_p)_{nf} = (1 - \varphi_v)(C_p)_f + \varphi_v(C)_p\qquad(5)$$

The heat transfer coefficient of the test fluid, h_i can be calculated by the following equation [9]:

$$\frac{1}{U_i} = \frac{1}{h_i} + \frac{D_i Ln\frac{D_o}{D_i}}{2k_w} + \frac{D_i}{D_o} + \frac{1}{h_o}\qquad(6)$$

Where D_i and D_o are the inner and outer diameters of tubes ,respectively. U_i is the overall heat transfer coefficient based on the inside tube area, h_i and h_o are the individual convective heat transfer coefficients of the fluids inside and outside the tubes, respectively and k_w is the thermal conductivity of the tube wall. U_i is given by:

$$Q = U_i A_i \Delta T_{lm}\qquad(7)$$

Where $A_i = \pi D_i L$ and ΔT_{lm} is the logarithmic mean temperature difference. The convection heat transfer from the test section can be written by[10]:

$$Q_{(convection)} = h_i A_i ((T_{\widetilde{W}} - T_b)\qquad(8)$$

$$T_b = \frac{T_{out(nano\,fluid(hot\,fluid))} + T_{in(nano\,fluid(hot\,fluid))}}{2}\qquad(9)$$

$$\left(T_{\widetilde{W}} = \sum\frac{T_W}{4}\right)\qquad(10)$$

T_W is the local surface temperature at the outer wall of the inner tube .The average surface temperature $T_{\widetilde{W}}$ is calculated from 4 points of T_w lined between the inlet and the exit of the test tube.
The heat transfer coefficient, h_i and the Nusselt number, Nu are estimated as follows[11]:

$$h_i = \overset{\circ}{m}_{(nano\,fluid(hot\,fluid))}$$
$$C_{p(nano\,fluid(hot\,fluid))}\qquad(11)$$
$$(T_{out} - T_{in})/A_i((T_{\widetilde{W}} - T_b)$$

$$Nu_{nf} = \frac{h_i d_i}{k_{nf}}\qquad(12)$$

Where the effective thermal conductivity (k_{nf}) of the nanofluids can be evaluated by Timofeeva correlations model that is given as follows [12]:

$$k_{nf} = (1 + 3\varphi)k_w\qquad(13)$$

The thermal conductivity of the nanofluids is calculated from the Wasp [13] model, which is defined as follows:

$$k_{nf} = \left[\frac{k_p + 2k_{m-}2\varphi(k_w - k_p)}{k_p + 2k_{w+}\varphi(k_w - k_p)}\right]k_w\qquad(14)$$

Moreover, k_{nf} is the thermal conductivity of the nanofluid, k_p is the thermal conductivity of the nanoparticles, and k_m is the thermal conductivity of the base fluid.

Viscosity of the nanofluid is calculated using Einstein [14] correlations as below:

$$\mu_{nf} = (1 + 2.5\varphi)\mu_w \qquad (15)$$

Brinkman [15] suggested the equation for calculating the viscosity of the suspension, which is defined as follows:

$$\mu_{nf} = \frac{1}{(1-\varphi)^{2.5}}\mu_w \qquad (16)$$

The Reynolds number and Prandtl number of nanofluid are calculated using following relations[11]:

$$Re_{nf} = \frac{\rho_{nf}V_{nf}d_i}{\mu_{nf}} \qquad (17)$$

$$Pe_{nf} = \frac{\mu_{nf}Cp_{nf}}{K_{nf}} \qquad (18)$$

Where, V_{nf} is the average velocity of nanofluid flowing through the copper tube.

Nusselt number of the nanofluid flow is computed from the following equation:

$$Nu_{nf} = \frac{h_{nf}d_i}{K_{nf}} \qquad (19)$$

Similarly to the heat transfer coefficient, the friction factor of the nanofluid is calculated from[16]:

$$f_{nf} = \frac{2D\Delta P_{nf}l}{u_m^2 l\rho_{nf}} \qquad (20)$$

Where f_{nf} is the friction factor of the nanofluid, ΔP_{nf} is the measured pressure drop of the nanofluid, l is the length of the tube, D is the diameter of the tube, ρ_{nf} is the density of the nanofluid, and u_m is the mean velocity of the nanofluid.

The uncertainty values for different instruments are given in Table 2. Also, the maximum possible error for the parameters involved in the analysis are estimated and summarized in Table 3.

4.Experimental Results

Lots of experiments have been performed to evaluate the effect of adding nanoparticles to the base fluid on heat transfer coefficient and Nusselt number and the results have been reported. The results show that convection and overall heat transfer coefficient and Nusselt number are increased with addition of nanoparticles to the base fluid, however, this increase depends on concentration and size of nanoparticle, type of base fluid and Reynolds number. Figures 3 and 4 show that convection heat transfer is increased with the addition of Al_2O_3. Increasing flow rate, concentration and temperature will intensify this improvement.

As an example, heat transfer coefficients for Re=18000 and T=40^{0}C for water and with volume concentrations (nanoflouid) 0.1,0.2 and 0.3% are9256, 10800,11745 and 12235 respectively. At the same condition but for T=50^{0}C, the coefficients are10836, 11650,12740 and 13100, respectively.

This result proves that increasing temperature has great impact on increasing heat transfer coefficient. Calculated heat transfer coefficients for Re=2400 and T=40^{0}C for water and with volume concentrations of 0.1, 0.2 and 0.3% are 9800,11500,13100, and 13760 ,respectively. At the same condition but for T=50^{0}C, the coefficients are11000,12200, 14100, and 15400 respectively.
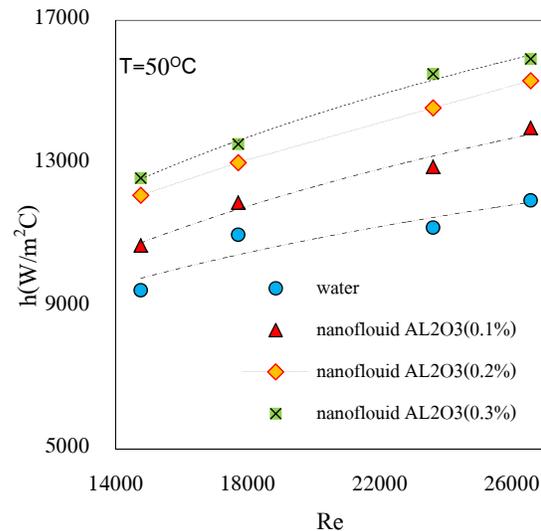

Fig. 3. Convective heat transfer coefficient of Al_2O_3/water nanofluid versus Reynolds number for different volume concentrations
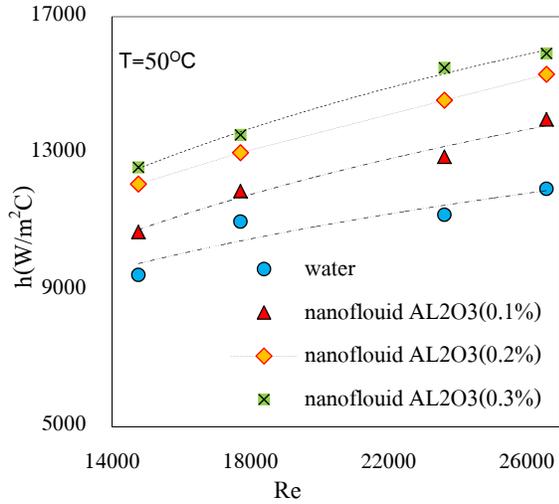
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Fig. 4. Convective heat transfer coefficient of Al_2O_3/water nanofluid versus Reynolds number for different volume concentrations

These results indicate that increasing flow rate will increase heat transfer coefficient. The same results can be expected for Nusselt number, too.

As seen in figures 5 and 6, the Nusselt number at T= 40^0C for water and the flow rate of 26700 with the volume concentrations of 0.1,0.2 and 0.3% are 135, 142.1, 160, and 172 in the same order as mentioned. At the same condition but for T=50^0C, the Nusselt number is 150,162,174, and 190 respectively. This results show that the nusselt number of nanofluid is 21% higher when compared with pure base fluid. The heat transfer enhancement due to nanofluids may be because of several factors such as improved effective thermal conductivity of the nanofluid as compared to base fluid, Brownian motion of nanoparticles, particle migration, reducing the thickness of the boundary layer and inducing turbulence motion. Heat transfer coefficient of nanofluid can be considered as a function of nanoparticle properties, concentration and size together with fluid flow rate. Collision and random motion of nano-particles and particles movement from high to low concentration region is an important contributing factor in heat transfer enhancement of nanofluids which, in turn, contributes to flatten the temperature profile. As a result, the temperature gradient at the wall becomes steeper and the heat transfer rate at the wall increases. In general ,adding nanoparticles by using three mechanisms will increase heat transfer:

a) Nano particles have higher heat guide and the higher density of particles ,more increase in heat transfer.

b) Nano particles with fluid molecule based on the wall and turned into heat and the cause of increase in energy.

c) Nano fluid friction between fluid and the wall tube increases and will improve heat exchange.

The intensity of the collision of particles in nano fluid with an increase in the fluid mass flow is more, that this would also increases the friction .Moreover, the type of nano-fluid and the properties of the walls of the heat exchanger can be determined.

One reason for this difference in heat transfer at high Reynolds numbers is the high viscosity of nano-rod fluid.
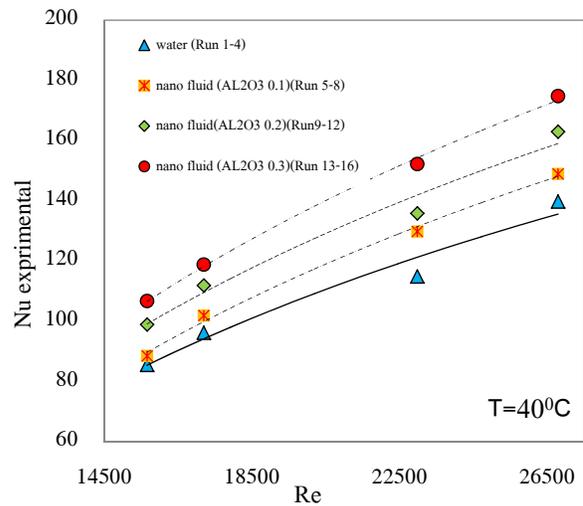

Fig.5. Nusselt number of Al_2O_3/water nanofluid versus Reynolds number for Different volume concentrations
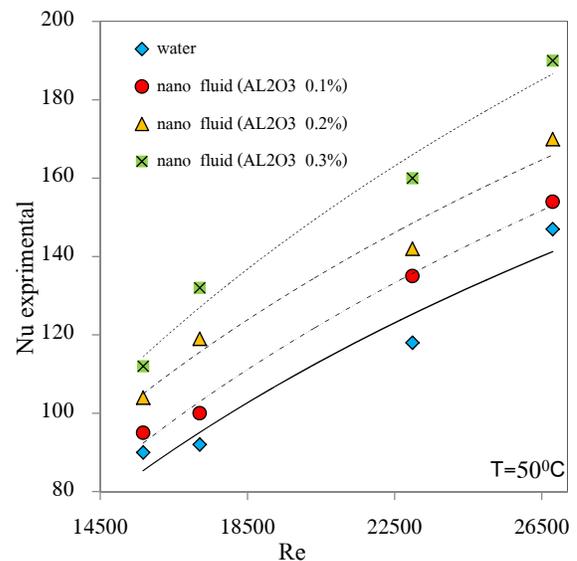

Fig. 6. Nusselt number of Al_2O_3/water nanofluid versus Reynolds number for Different volume concentrations

In general, the fluid containing rod-shaped particles, due to severe reactions has high viscosity and high density in shear flow. So this is also one of the factors reducing heat transfer to the rod-shaped nanoparticles. In this experiment, the spherical shape of the nanoparticles have been studied. Particle concentration and movement of particles in the flow are other factors that affect the heat transfer. Nanofluid is assumed that the main mechanism for increasing the thermal conductivity of nanoparticles is a transitional move. The mobility of smaller particles than for larger particles increases the coefficient of thermal conductivity of nanofluids.

As shown in figures 7 and 8, the overall heat transfer coefficient at T=40^{0}C for water and the Reynolds number of 15000 and 27000 with the volume concentrations of 0.1,0.2 and 0.3% are 2020, 2400, 2550, 2600, 2630, 2880, 2930 and 2970 respectively. At the same condition but for T=50^{0}C, the overall heat transfer coefficients are, 2430, 2500, 2550, 2590, 2850 , 2900, 2980, and 2930 respectively. The increase in overall heat transfer coefficient can be attributed to the chaotic motion and migration of nanoparticles , reduction of boundary layer thickness, and delay in boundary layer development due to the fluid viscosity.
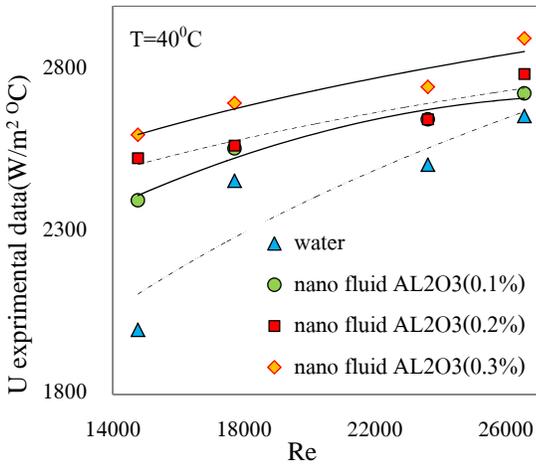

Fig. 7. Overall heat transfer coefficient of Al$_2$O$_3$/water nanofluid versus Reynolds Number for various volume concentrations

In general, Nusselt numbers of nanofluids may be related with the parameters as follows (equation 21). Considering the above mentioned equation, the equation for predicting the heat transfer performance of nanofluid was formed and is proposed in the following form equation 22.
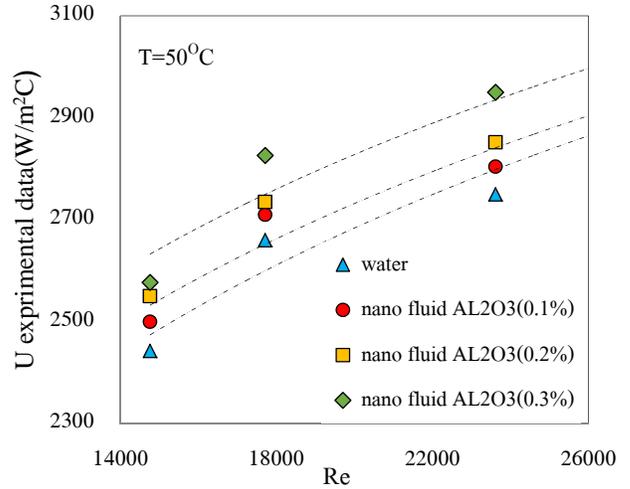

Fig. 8. Overall heat transfer coefficient of Al$_2$O$_3$/water nanofluid versus Reynolds Number for various volume concentrations

$$Nu_{nf} = f(Re_{nf}, Pr_{nf}, \varphi) \tag{21}$$

$$Nu = 0.074 Re^{0.707} Pr^{0.385} \varphi^{0.074} \tag{22}$$

As shown in figure 9, the results show that the present correlation gave reasonably good agreement with the experimental data. This equation can be used to compute Nusslte number of nanofluids with particle volume concentrations range between 0.1% vol and 0.3 vol% The results show good correspondence between the experimental values and the calculated values by the above equation. It is clearly seen that the majority of the data falls within ±10% of the proposed.
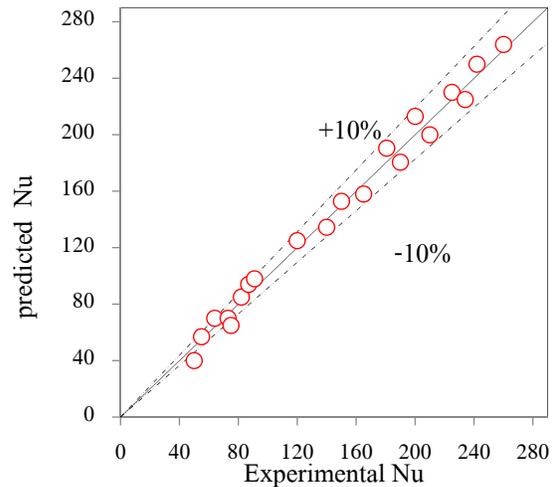

Fig. 9. Comparison between Nu measured and Nu predicted by correlation

5. Conclusion

Experimental results with the Aluminum Oxide nanofluid heat exchanger in the range of (0.1-0.3% vol) with a size of 20 nm can be summarized as follows:

1-Overall heat transfer coefficient of the flow increases from 8% to 44**%** for Aluminum Oxide nanofluid with concentrations of 0.1 vol % to 0.3 vol %.

2-Convective heat transfer coefficient of the flow also increases from 13% to 69% for Aluminum Oxide nanofluid with concentrations of 0.1 vol % to 0.3 vol %.

3- Nusselt number of the flow increases from 30% to 84% for Aluminum Oxide nanofluid with concentrations of 0.1 vol% to 0.3 vol %.

4-The pressure drop of nanofluid increases with increasing Reynolds number and there is a slight increase with increasing particle concentrations. This is caused by increase in the viscosity of nanofluid, and it means that nanofluid incur little penalty in pressure drop.

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