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Heat Transfer of Iron Oxide Nanofluid in a Double Pipe Heat Exchanger

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Abstract

This article reports experimentally the convection heat transfer coefficient and Nusselt number of the Fe_3O_4-water nanofluids flowing in a double pipe heat exchanger under turbulent flow *(14000≤Re≤34600)* conditions. Fe_3O_4 nanoparticles with diameters of 15-20 nm dispersed in water with volume concentrations of 0.08≤φ≤ 0.1 vol. % are used as the test fluid. The results show that the convection heat transfer coefficient and Nusselt number of nanofluid was approximately 12 -26% greater than that of pure fluid. In addition, the heat transfer coefficients and Nusselt number increases with increase in flow rate, nanoparticle concentration and nanofluid temperature. Comparison of experimental results with valid theoretical data based on semi-empirical equations shows an acceptable agreement .

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

Introduction

The addition of solid particles into heat transfer media has long been known as one of the useful techniques for enhancing heat transfer, although a major consideration when using suspended millimeter-or micrometer-sized particles is that they have the potential to cause some severe problems, such as abrasion, clogging, high pressure drop, and sedimentation of particles. Comparedto heat transfer enhancement through the use of suspended large particles, the use of nanoparticles in the fluids exhibited better properties relating to the heat transfer of fluid. This is because nanoparticles are usually used at very low concentrations and nanometer sizes. These properties prevent the sedimentation in the flow that may clog the channel. From these points of view, there have been some previous studies conducted on the heat transfer of nanoparticles in suspension.Since Choi et al. wrote the first review article on nanofluids [1]. Nguyen et al. [2] investigated the heat transfer coefficient and fluid flow characteristic of Al_2O_3nanoparticles dispersed in water flowing through a liquid cooling system of microprocessors under turbulent flow condition. 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. He et al [3] reported an experimentally study that investigated 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. Aghayari et al. [4] reported experimental results which illustrated the dispersion of the heat

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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. 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.

O.S. Prajapati et al. [11] investigated on nanofluids indicate that the suspended nanoparticles markedly change the heat transfer characteristics of the suspension. In this study, heat transfer characteristics of ZnO-water nanofluids were investigated. Experiments were conducted with ZnO-water nanofluids at particle volume concentrations up to 0.1 volume %, constant subcooling of 20°C, pressure 2 bar, mass flux 400 kg/m^{2}s and heat fluxes up to 500 kW/m^2 with variable. Effect of heat flux and nanofluid concentration on heat transfer coefficient of ZnO-water nanofluids was investigated. Study reveals that heat transfer coefficient increases with ZnO-water nanofluids.

K.B. Rana et al.[12] reports an experimental study on the pressure drop characteristics of ZnO-water nanofluids through the horizontal annulus. Experiments were performed in single phase and boiling flow of nanofluids under turbulent flow with different low particle concentrations(≤0.01 vol. %). Experiments were conducted at flow rates from 0.1 to 0.175 lps, heat fluxes from 0 to 550 kW/m^2 and 1 bar constant inlet pressure. The results show that the pressure drop of the nanofluids is very close to that of the base liquid flows for given flow rates. The pressure drop of the water and nanofluids increases with an increase in the flow rate and remains almost constant with increase in the heat flux.

Experimental

Experimental setup

The experimental investigation of heat transfer characteristic of nanofluid was carried out using the experimental apparatus as shown in figure 1. It mainly consists of a test section, receiving tanks in which working fluids are stored, heating and cooling system, thermometer, flow meter, Rota-meter, pressure measurement system and data acquisition system. The working fluids were circulated through the loop by using variable speed pumps of suitable capacity. The test section is of 1.2 m length with counter flow path within horizontal double pipe heat exchanger in which hot nanofluid was applied inside the tube while cooling water was directed through the annulus. The inside pipe is made of a soft steel tube with the inner diameter of 6mm, outer diameter of 0.008m and thickness of 0.002m while the outside pipe is of steel tube with the inner diameter of 0.014m,outer diameter of 0.016 m and thickness of 0.002m. To measure the inlet and outlet temperature of the nanofluid and cold water at the inlet and outlet of the test section, 4 thermocouples of type J were used. All of the thermocouples were calibrated before fixing them. 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 All four evaluated temperature probes were connected to the data logger sets. An electric heater and a thermostat installed on it were used to maintain the temperature of the nanofluid. During the test, the mass flow rate and the inlet and outlet temperatures of the nanofluid and cold water were measured. To measure the pressure drop across the test section, differential pressure transmitter was mounted at the pressure tab located at the inlet and outlet of the section. The nanofluid flow rate was measured by a magnetic flow meter which was placed at the entrance of the test section. For each test run, it was essential to record the data of the temperature, volumetric flow rates and pressure drop across the section at steady state conditions. Two storage tanks made of stainless steel at capacity of 15 lit were used to collect the fluids leaving the test section. To ensure the steady state condition for each run, the period of around 15-20 minutes depending on Reynolds number was taken prior to the data record.

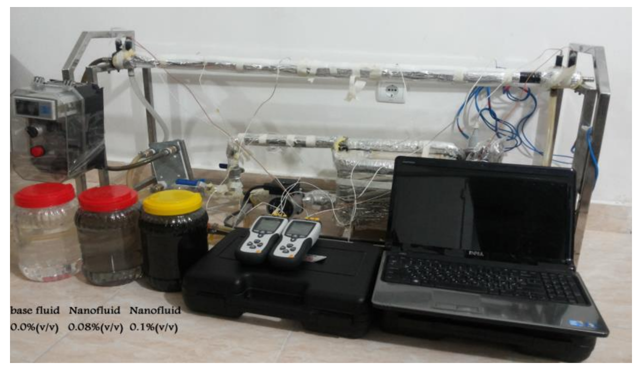


Figure 1: Schematic diagram of the experimental setup.

Nanofluid preparation

The nanofluid used in the experiment was 99.0+% pure iron oxide predispersed in water, with an average particle size of 15-20 nm. The nanofluid was mixed with deionized water. To prepare experimental concentrations, nanofluids with less than 3% nanoparticles were found to be stable and the stability lasted over a week; no intermediate mixing was considered necessary . The volume fraction of Fe_3O_4 nano-particles in nanofluid samples varied from 0.08 and 0.1% v/v. NF samples were then underwent mixing by ultra-sonic method between 3 to 4 hours to ensure complete dispersion is achieved. The morphology of Fe_3O_4 nano-particles was studied by using SEM.(Figure 2). The volume concentration is evaluated from the following relation in percentage:

$$\varphi_v = \frac{Volume\ of\ Fe_3O_4}{Volume\ of\ Fe_3O_4 + Volume\ of\ water} \times 100 \qquad (1)$$

$$\varphi_v = \frac{\frac{W_{Fe_3O_4}}{\rho_{Fe_3O_4}}}{[\left(\frac{W_{Fe_3O_4}}{\rho_{Fe_3O_4}}\right) + \left(\frac{W_{water}}{\rho_{water}}\right)]} \times 100 \qquad (2)$$

Where ρ_{Fe3O4} is density of Fe_3O_4, ρ_{water} is density of water and φ_v is the volume concentration.

Data processing

The experimental data were used to calculate convective heat transfer coefficient and Nusselt number of nanofluids with various particle volume concentrations and Peclet numbers. For fluid flows in a concentric tube heat exchanger, the heat transfer rate of the hot fluid (nano fluid Fe_3O_4) in the inner tube can be expressed as:

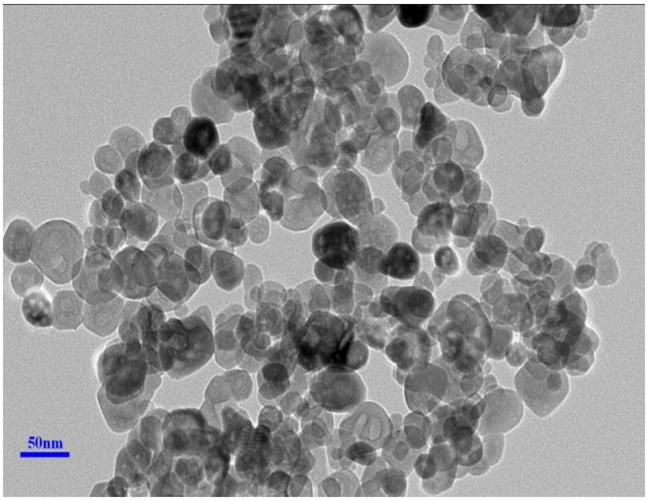


Figure 2: SEM photograph of Fe_3O_4 particles

$$Q_{(\text{nano fluid(hot fluid)})} = \overset{\circ}{m}_{(\text{nano fluid(hot fluid)})} C_{p(\text{nano fluid(hot fluid)})} (T_{out} - T_{in}) \quad (3)$$

Where m° 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:

$$Q_{(\text{cold fluid(water)})} = \overset{\circ}{m}_{(\text{cold fluid(water)})} C_{p(\text{cold fluid(water)})} (T_{in} - T_{out}) \quad (4)$$

Where m° is the mass flow rate of the water (cold fluid), and T_{out} and T_{in} are the outlet and inlet temperatures of the water (cold fluid), respectively.

The effective density of nanofluid is:

$$\rho_{nf} = (1 - \varphi_V)\rho_f + \varphi_v \rho_p \quad (5)$$

Subscripts f, p, and nf refer to the base fluid, the nanoparticles, and the nanofluid, respectively. φ_v is the nono particle volume concentration. C_{pnf} is the effective specific heat of the nanofluid which can be calculated from Xuan and Roetzel relation [5]:

$$(\rho C_p)_{nf} = (1 - \varphi_v)(\rho C_p)_f + \varphi_v (\rho C)_p \quad (6)$$

The heat transfer coefficient of the test fluid, h_i, can be calculated by the following equation [6]:

$$\frac{1}{U_i} = \frac{1}{h_i} + \frac{D_i Ln\frac{D_o}{D_i}}{2k_w} + \frac{D_i}{D_o} + \frac{1}{h_o} \quad (7)$$

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:

$$Q = U_i A_i \Delta T_{lm} \quad (8)$$

Where $A_i = \pi D_i L$ and ΔT_{lm} is the logarithmic mean temperature difference. The outside heat transfer coefficient can be computed by Bell's procedure [7].Nusselt number of nanofluids is defined as:

The convection heat transfer from the test section can be written by:

$$Q_{(\text{convection})} = h_i A_i ((T_{\tilde{W}} - T_b) \quad (9)$$

$$T_b = \frac{T_{out(\text{nano fluid(hot fluid)})} + T_{in(\text{nano fluid(hot fluid)})}}{2} \quad (10)$$

$$\left(T_{\tilde{W}} = \Sigma \frac{T_W}{6}\right) \quad (11)$$

T_w is the local surface temperature at the outer wall of the inner tube .The average surface temperature $T_{\tilde{W}}$ 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:

$$h_i = \overset{\circ}{m}_{(\text{nano fluid(hot fluid)})} C_{p(\text{nano fluid(hot fluid)})} (T_{out} - T_{in}) / A_i ((T_{\tilde{W}} - T_b) \quad (12)$$

$$Nu_{nf} = \frac{h_i d_i}{k_{nf}} \quad (13)$$

Where the effective thermal conductivity (k_{nf}) of the nanofluids can be evaluated by Maxwell's model that is given as following [8]:

$$k_{nf} = k_f \frac{k_P + 2k_f - 2\varphi_V(k_f - k_p)}{k_p + 2k_f + \varphi_V(k_f - k_p)} \quad (14)$$

Maxwell's formula shows that the effective thermal conductivity of nanofluids (k_{nf}) relies on the thermal conductivity of spherical particles (k_p), the thermal conductivity of base fluid (k_f) and volume concentration of the solid particles (φ_v).

The uncertainty values for different instruments are given in Table 1. Also, the maximum possible error for the parameters in volved in the analysis are estimated and summarized in Table 2.

Table 1: Uncertainties of experimental instruments.

Name of instrument	Range of instrume-nt	Variable measured	Least division in measurin-g instrume-nt	Min. and max. values measured in experimen-ts	Uncertainty(%)
Thermocouple	-200 to 1372 °C	Balk temperature	0.1 °C	30-55°C	0.361
Thermocouple	-30 to 550 °C	Wall temperature	0.1 °C	30-50°C	0.279
Flow meter	0-0.16 gr/s	Volumetric flow rate	0.001 gr/s	0.01 - 0.15 gr/s	0.678

Table 2: Uncertainties of experimental parameters.

Parameter name	Uncertainty error(%)
Convective heat transfer coefficient	2.45
Nusselt number	3.21

Results and Discussion

To evaluate the accuracy of the measurements, experimental system was tested with distilled water before measuring the convective heat transfer of nanofluids. Fig. 3 shows the comparison between the measured Nusselt number and prediction of Eq. (15) in which h_i is evaluated by Gnielinski correlation for turbulent flow through a tube [9]:

$$Nu = 0.012(Re^{0.87} - 280)Pr^{0.4} \quad (15)$$

As shown in Fig. 3, the good agreement exists between the experimental data and predicted values.

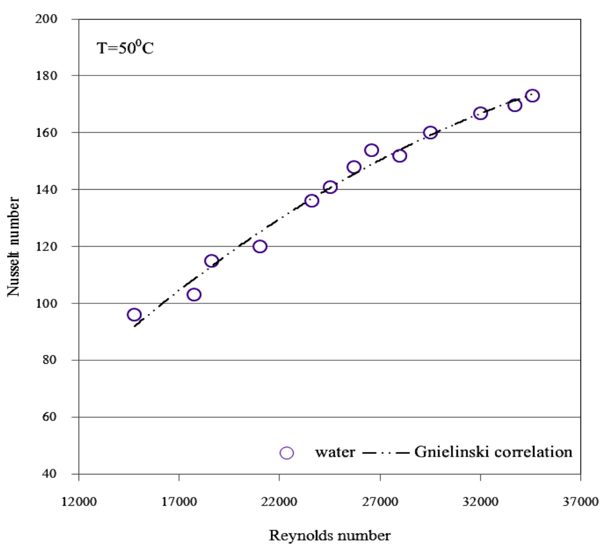


Figure 3: Comparison between the measured Nusselt number and predicted values for distilled water.

Comparison of convective heat transfer coefficient between the nanofluid and the base fluid shows that this value is higher for the nanofluid at the same Reynolds number than the base fluid Figure 4(a,b).This results in the increase of heat transfer efficiency caused by the increase of thermal conductivity, convective heat transfer and the thikness of thermal boundary layer.

The possible reasons for this increase may be as follows:

1.A nanofluid with suspended nano-particles increases the thermal conductivity of the mixture.

2. High Energy exchange process, which is resulted from the amorphous movement of the nanoparticles.

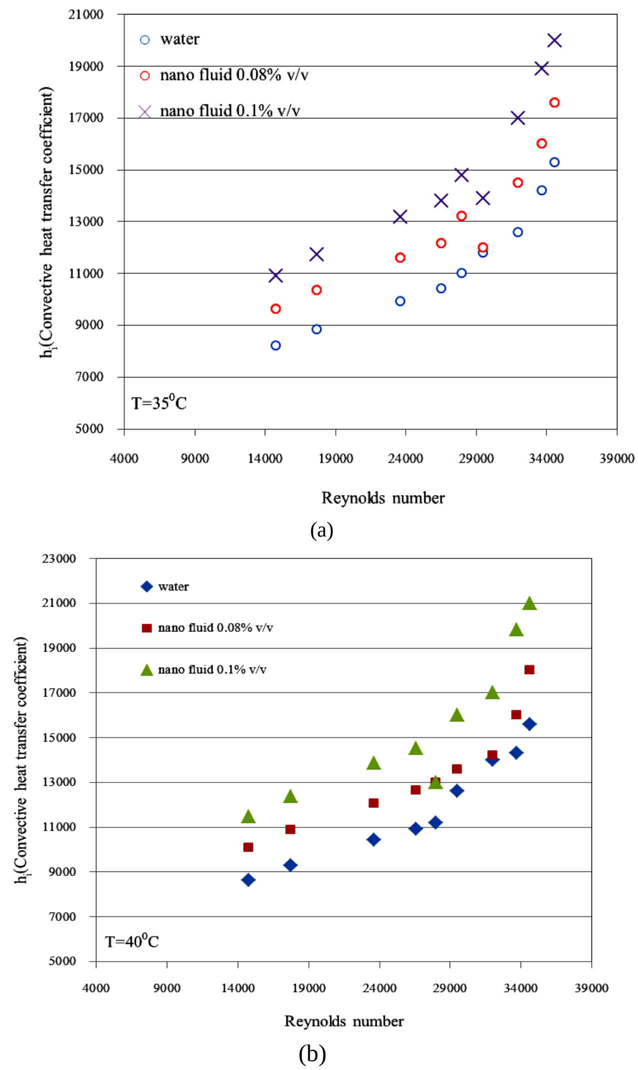


Figure 4: Convective heat transfer coefficient of Fe_3O_4/water nanofluid versus Reynolds number for different volume concentrations.

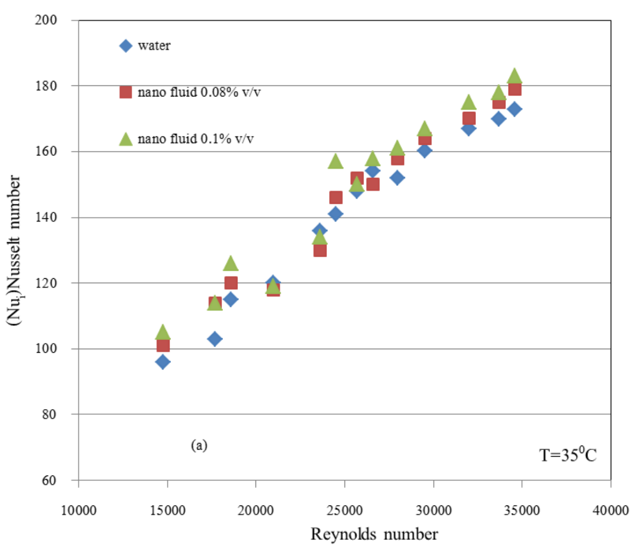
Figure 5(a,b) shows the effects of temperature and concentration of iron Oxide nanofluid in terms of the Nusselt number at the temperatures of 35 and 40°C, respectively. As can be seen, Nusselt number of the nanofluid under the condition of same Reynolds number is greater than the base fluid. For example, this value is 19%for the nanofluid with a concentration of 0.1 at the temperature of 35°C compared to the base fluid (the Reynolds number of 26500). This amount is 25% at the temperature of 40°C .This increase can be attributed to the thermal conductivity. There are several mechanisms to increase the thermal conductivity of the nanofluid: the formation of the liquid layer on the surface of the nanoparticles, Brownian motion, classification of particles, the transmission of the phonons projectiles in the nanoparticles, the increase of the thermal conductivity of fluids with the increase of the nanoparticles in the pipe wall. The increase in the thermal conductivity can increase the heat transfer coefficient in the thermal boundary layer near the tube wall. Temperature is one of the factors increasing the thermal conductivity of the nanofluid and thereby increasing the heat transfer coefficient and Nusselt number. Experimental results indicate that the effects of the nanoparticles on the thermal conductivity increases with the temperature. It is assumed that the main mechanism for the thermal conductivity of the nanofluid is the random motion of the nanoparticles. This pseudo-Brownian motion is a function of fluid temperature. Thus, the increase in the thermal conductivity is higher for smaller particles than for larger particles at the high temperatures. Brownian motion at low temperatures is of less importance and therefore the difference in the increase of the thermal conductivity between the smaller and larger particles is reduced.

Comparison between experimental results and available correlations

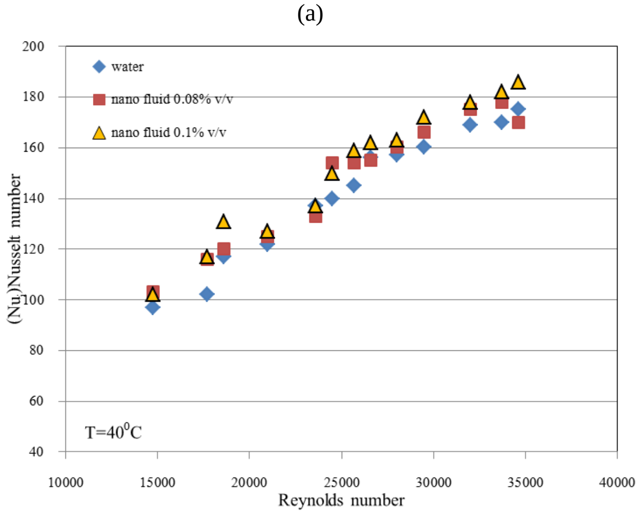
In Figs. 6. the experimental results for the Nusselt number of Fe_3O_4/water nanofluid is compared with the prediction of Xuan and Li correlation. The correlation was provided By Xuan and Li for turbulent flow of nanofluid inside a tube[10]:

$$Nu_{nf} = 0.0059(1 + 7.6286\varphi_V^{0.6886} Pe_p^{0.001}) Re_{nf}^{0.9238} Pr_{nf}^{0.4} \quad (16)$$

As seen in Figure 6, there is an agreement between the experimental and calculated values for nanofluid. In the present study, iron oxide nanoparticles mixed with water to the volume percent of 0.08-0.1%(v/v) are used to investigate the effects of Reynolds number, the temperature of the flowing nanofluid and the nanoparticle concentration on the heat transfer. Nusselt number increases with the Reynolds number. The obtained results are consistent with the results from the relationship between Li and Xuan [10].



(a)



(b)

Figure 5: Nusselt number of Fe_3O_4/water nanofluid versus Reynolds number for Different volume concentrations

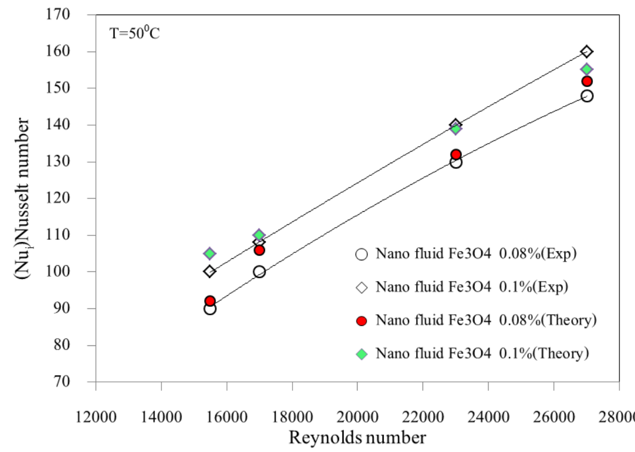


Figure 6: Comparison between the experimental results and calculated values from correlation (16) for Fe_3O_4/water nanofluids.

Conclusions

Experimental results with the iron oxide nano-fluid heat exchanger in the range of (0.08-0.1% vol) with a size of 15-20 nm can be summarized as follows:

1. Convective heat transfer coefficient of the flow also increases from 13% to 28% for iron oxide nanofluid for concentrations of 0.08 vol % to 0.1 vol %.
2. Nusselt number of the flow also increases from 10% to 24% iron oxide nanofluid for concentrations of 0.08 vol% to 0.1 vol %.

This study investigated the heat transfer enhancement of the nanofluid containing iron oxide nanoparticles and water under the condition of turbulent flow in a double pipe heat exchanger. The heat transfer values were measured in the turbulent flow of a nanofluid containing 15-20 nm iron oxide suspended particles with the volume concentration of (0.08-0.1%)(v/v) in water.Properties of nanofluid are good and there is plenty of fluid. Heat transfer coefficient and Nusselt number of the nanofluid increase from 10 to 27% compared to the base fluid according to the comparison on the basis of fixed Reynolds number. Experimental results showed the increase of the average heat transfer coefficient in the turbulent flow regime with the addition of the nanoparticles to the fluid.The obtained results are in agreement with the results from the relationship between Li and Xuan [10]. This increase in the heat transfer coefficient may be due to the high density of nanoparticles on the wall pipe and the migration of the particles. The extensive research is needed to understand the heat transfer characteristics of the nanofluid and to obtain the other relations.One of the reasons for the increase in heat transfer fluid nano iron oxide surface structure and shape of nanoparticles is compared to the base fluid. iron oxide nanoparticles that were examined in this experiment has a spherical shape and is the property of hydrophobicity on the stability of these factors affect the distribution of particles in the base fluid. But if a rod-shaped nanoparticles mode and aspect ratio is the factor that affects the heat transfer system. As a result, the heat transfer increases somewhat, but the amount is very less in comparison to the globular state.

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