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EXPERMENTAL INVESTIGATION OF CONVECTIVE HEAT TRANSFER OF NANOFLUIDS

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ABSTRACT

Nanofluids, i.e. fluid suspensions of nanometer-sized particles and fibers, have been currently proposed as a method for increasing the performance of heat transfer in nanofluids and the effect of nanoparticles on convective heat transfer coefficient and different results are attained. Present work is about the design and manufacturing an experimental set up to study the enhancement of heat transfer coefficient of nanofluid on laminar convective heat transfer. Forced convection heat transfer of water-Al_2O_3, water-TiO_2 and water-SiO_2 nanofluids inside a circular tube with uniform heat flux was investigated experimentally. Experimental results emphasize the enhancement of heat transfer due to the nanoparticles presence in the fluid. Values of Nusselt number were obtained and these results have been introduced by experimental correlations.

INTRODUCTION

Cooling technology is one of the most important challenges for modern industries, such as microelectronics, transportation, and manufacturing. Technological developments in microelectronic devices with small (sub-100 nm) features and faster (multi-gigahertz) operating speeds, higher-power engines, and brighter optical devices cause thermal load increasing which require more innovative techniques of heat dissipation. Using nanofluids has been suggested as a new heat transfer fluid.

The term of nanofluids refers to a new kind of fluids by suspending nanoparticles in base fluids. This term was used by Choi [1]. Nanofluids are considered to be the next-generation heat transfer fluid as they provide new possibilities to enhance heat transfer performance compared to pure liquids. Nanofluids are expected to have superior thermophysical properties compared to conventional heat transfer fluids. The larger relative surface area of nanoparticles, compared to those of conventional particles, would not only improve significantly heat transfer capabilities, but also increase the stability of the suspensions. Nanofluids can also improve abrasion-related properties compared to the conventional micro sized solid/fluid mixtures. For example, it's reported that a few amount (less than 1% volume fraction) of Cu nanoparticles or carbon nanotubes dispersed in ethylene glycol or oil would increase the inherently poor thermal conductivity of the liquid by 40% and 150%, respectively [2, 3]. Conventional micro size particle - liquid suspensions require high concentrations (greater than 10%) of particles to achieve such enhancement. These suspensions had not extensive applications due to problems such as sedimentation, erosion, fouling and increased pressure drop of the flow channel. Due to these problems, the use of suspended nanoparticles becomes more attractive. Their ultra-fine size can lead to suspensions with low particle concentrations. Therefore, the suspensions are free from sedimentation that might clog the flow channel. They are also expected to cause little or no pressure drop losses.

During previous decade many research activities have been made in heat transfer enhancement of various nanofluids. Xuan and Li [4] experimentally investigated flow and convective heat transfer characteristics for Cu–water based nanofluids through a straight tube with a constant heat flux at wall. Results showed that the nanofluids give substantial enhancement of heat transfer rate compared to pure water. They also claimed that the friction factor for the nanofluids at low volume fraction did not produce extra losses in the pumping power.

Wen and Ding [5] reported experimental results for the convective heat transfer of γ -Al_2O_3 (27–56 nm)/water based nanofluids flowing through a copper tube (D = 4.5 mm, L = 970 mm) in laminar regime. They found that the presence of Al_2O_3 particles can significantly enhance the convective heat transfer coefficient, which augments with increasing Reynolds number and particle concentrations. Furthermore, the improvement of the heat transfer coefficient is particularly large in the entrance region, and decreases with the axial distance.

Ding et al. [6] investigated the heat transfer performance of carbon nanotube (CNT) nanofluids in a tube with 4.5 mm inner diameter. They found that the observed enhancement of heat transfer coefficient is much higher than the increase in the effective thermal conductivity. They associated the possible reasons with the improved thermal conductivity, shear-induced enhancement in flow, reduced boundary layer, particle re-arrangement, and high aspect ratio of CNTs. These observations suggest that the aspect ratio should be associated with the high enhancement of heat transfer performance of CNTs-based nanofluids.

However, there are some contradictory reports on nanofluid behavior in forced convection. Pak and Cho [7] studied heat transfer performance of γ-Al2O3 – (13 nm) and TiO2 – (27 nm) water based nanofluids in tube. They found that the convective heat transfer coefficient of the nanofluids at $\varphi = 3$ vol% was 12% lower than pure water for a constant average velocity. It is possibly because the suspensions have higher viscosity than pure water, especially at high particle volume fractions.

Previous studies [4, 5, 7] with nearly spherical nanoparticles showed an enhancement of the convective heat transfer up to 60%. Results on CNTs nanofluids [6] increased the convective heat transfer coefficient over 350% at $Re = 800$ for 0.5 wt% CNTs.

Behzadmehr et al. [8] also has done an interesting numerical study on modeling forced convective heat transfer in a circular tube with constant heat flux. In this study, two phase mixture approach was used for turbulent flow and comprehensive comparing with single phase model was performed. The results showed that two phase model is more precise and compatible with experimental results than single phase model.

NOMENCLATURE

D	[mm]	Diameter of tube
C	[J/kgK]	Specific heat
h	[W/m^{2}K]	Heat transfer coefficient
hr	[-]	Convective heat transfer ratio
k	[W/mK]	Thermal conductivity
L	[mm]	Length of tube
$\dot{m}$	[kg s^{-1}]	Mass flow rate
Nu	[-]	Nusselt number, Nu = hD/k
$\overline{Nu}$	[-]	Average Nusselt number
Nur	[-]	Nusselt number ratio
P	[m]	perimeter
Pe	[-]	Peclet number, Pe = RePr
Pr	[-]	Prandtl number, Pr = Cpμ/k
Q	[W]	Heat rate
q"	[W/m^2]	heat flux
Re	[-]	Reynolds number, Re = ρVD/μ
T	[K]	Temperature
x	[mm]	Distance from entrance of pipe

Special characters

v	[m2/s]	Kinematic viscosity
φ	[-]	Volume fraction of nanoparticles in suspension
Φ	[-]	Mass fraction of nanoparticles in suspension
ρ	[kg/m3]	Density
μ	[kg/ms]	Viscosity

Subscripts

b	Base fluid
nf	Nanofluid
p	Particle
conv	Convection
w	Water
i	Pipe inlet
o	Pipe outlet
m	Bulk

EXPERIMENTAL SET UP

This test rig as shown in Figure 1 consist of different parts such as test section, cooling system, pump and flow control, flow velocity measurement, blending system, ultrasonic vibrator, heater, insulation and power control.

In fact test section consists of a 3m-tube with ten PT100 thermal sensors on its surface and two PT100 thermal sensors for measuring inlet and outlet temperatures.

This copper tube is covered with heater coil which is in wire shape. This heater has a cover and was flexible. Heater is insulated to provide constant heat flux.

Heat transfer with the surrounding has to be made through a heat exchanger to ensure the circulation of nanofluid flow in a closed loop in the experimental set up. For this reason, it's necessary to return nanofluid to its initial conditions and the system reaches the steady state.

Evidently a proper pump with sufficient pressure head is necessary for flow establishment in the tubes; a dimmer is used to control the power.

There is a sensor at 10cm of the pipe inlet to measure inner temperature of water (sensor1) and after 60cm of pipe inlet; the first surface sensor is placed. Other 9 surface sensors are placed every 25cm apart. Afterwards a sensor is placed 10cm before the end to show outlet water temperature.

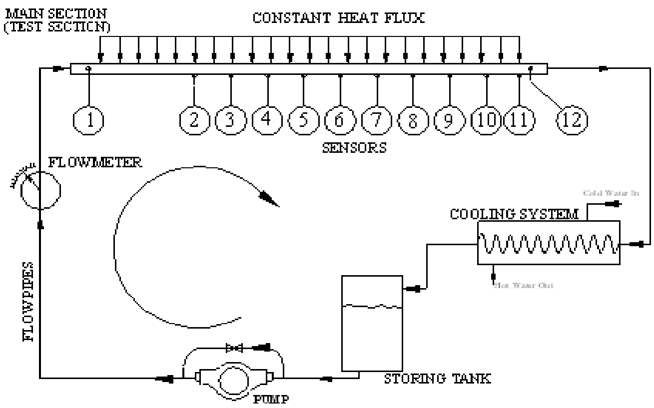

Figure 1 Schematic laboratory system

EXPERIMENTAL MODELING

In order to be certain about the laminar flow regime, tests are done for Reynolds numbers less than 2000.

Total heat transfer related to flow is calculated from equations 1 and 2:

$$dq_{conv} = \dot{m}c dT_m \quad (1)$$

$$q_{conv} = \dot{m}c(T_{m,o} - T_{m,i}) \quad (2)$$

As the heat flux is constant, we have

$$T_m(x) = T_{m,i} + \frac{\ddot{q}P}{\dot{m}c}x \quad (3)$$

In order to calculate ρ, μ, k and C of nanofluid, following equations are used [9].

$$\rho_{nf} = \varphi\rho_p + (1-\varphi)\rho_w \quad (4)$$

$$\mu_{nf} = (1 + 2.5\varphi)\mu_w \quad (5)$$

$$k_{nf} = \frac{k_p + 2k_w + 2(k_p - k_w) \times 1.1^3\varphi}{k_p + 2k_w - (k_p - k_w) \times 1.1^3\varphi} \quad (6)$$

$$c_{nf} = \varphi c_p + (1-\varphi)c_w \quad (7)$$

The hydrodynamical entrance length is 0.04DRe and thermal length is 0.04DRePr [10] and as Prandtl number in these tests is greater than 1, thermal entrance length is more than 1. In fact after the entrance length a fully developed flow is established.

In these tests for the least Reynolds number, 275, all thermal sensors are in fully developed region. It's also clear from Figure 2 that in this case, the Nusselt number for DI[1] water is obtained 4.407 and the difference from its value in reference [11], 4.364, is 0.985% which shows the accuracy of this set up.

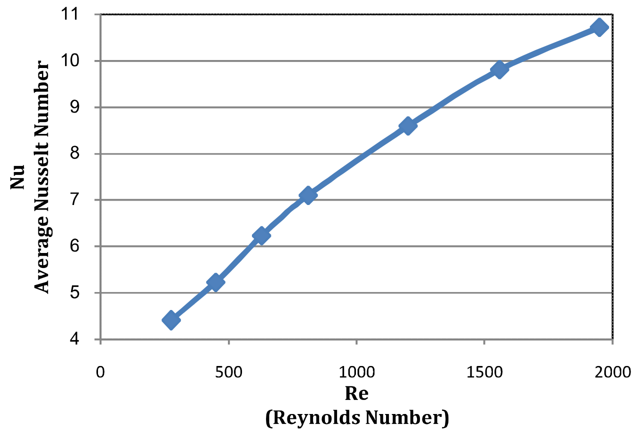

Figure 2 Average Nusselt number versus Reynolds number for DI water

In Figure 3 the results obtained from present experiments on water-Al_2O_3 nanofluid with 0.3% volume fraction have been compared to Hwang et al. [12] study. In this plot vertical axis represents convective heat transfer coefficient ratio and horizontal axis is Reynolds number. Results have a deviation less than 0.47%.

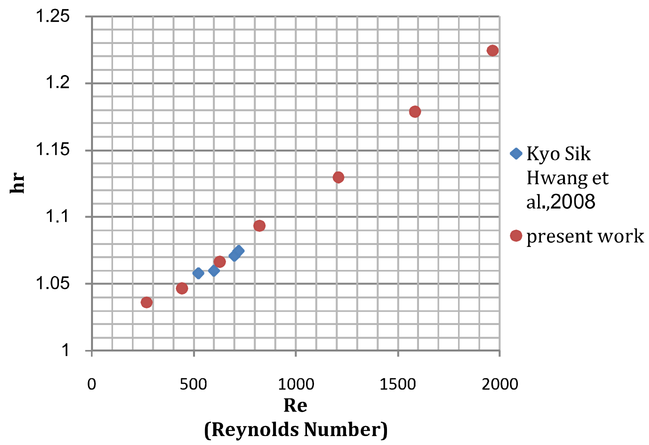

Figure 3 Comparison of convective heat transfer coefficient ratio between present results and another study for water-Al_2O_3 nanofluid with $\varphi = 0.3\ \%vol$

Figure 4 shows another comparison with previous study [12] and good agreement with less than 0.58% difference is observed. It has to be mentioned that Sodium Dodecylbenzene Sulfonate (SDBS) in amount of 0.1 mass fractions is used as an additive in water-Al_2O_3 nanofluid preparation process.

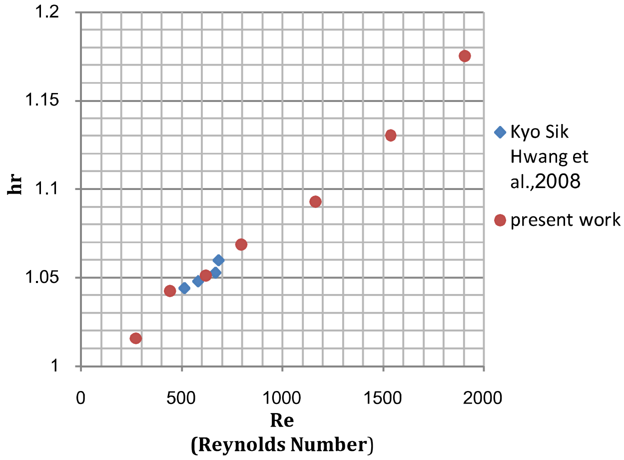

Figure 4 Comparison of convective heat transfer coefficient ratio between present results and another study for water-Al_2O_3 nanofluid with $\varphi = 0.2\ \%vol$

To prepare the nanofluid water-Al_2O_3, mechanical blender and ultrasonic vibrator are used. Mechanical blender is initially used and nanopowder is gradually added to water. Then ultrasonic vibrator is used to disperse better nanoparticles. It takes about 4 to 5 hours to prepare a stable and suitable nanofluid for each experiment.

Figure 5 illustrates the ratio of average Nusselt number to D.I. water called Nur versus Reynolds number in different concentrations for water-Al_2O_3 nanofluid. We can see from Figure 5 that average Nusselt number increases with increase of Reynolds number and concentration. It seems that the slop of plots change after Re=810. It is probably because all sensors are in entrance region.

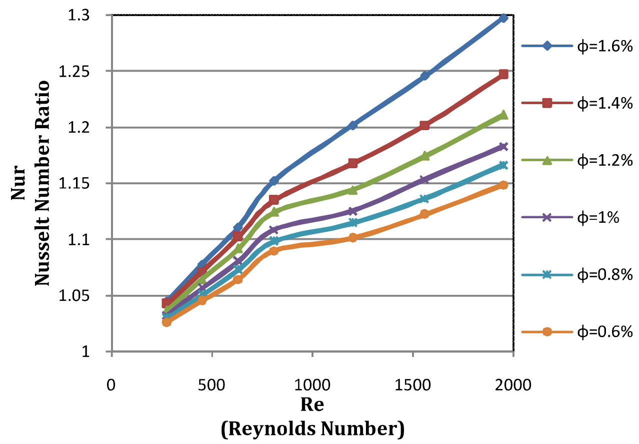

Figure 5 Plot of ratio of average Nusselt number to water versus Reynolds number for water-Al_2O_3 nanofluid in different concentrations

[1] Deionised

Figure 6 illustrates SEM image of Al_2O_3 nanoparticles in water for different concentrations. This image shows that nanoparticles are dispersed moderately in base fluid.

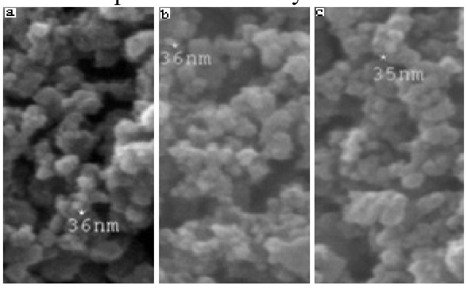

Figure 6 SEM image of water-Al_2O_3 nanofluid with a) 0.4% b) 0.8% c) 1.6% mass fraction

Figure 7 illustrates the ratio of average Nusselt number versus nanoparticles concentration for different Reynolds numbers of water-Al_2O_3 nanofluid. It is shown that an enhancement of 30% in Nusselt number is achievable using water-Al_2O_3 nanofluid with 1.6% concentration.

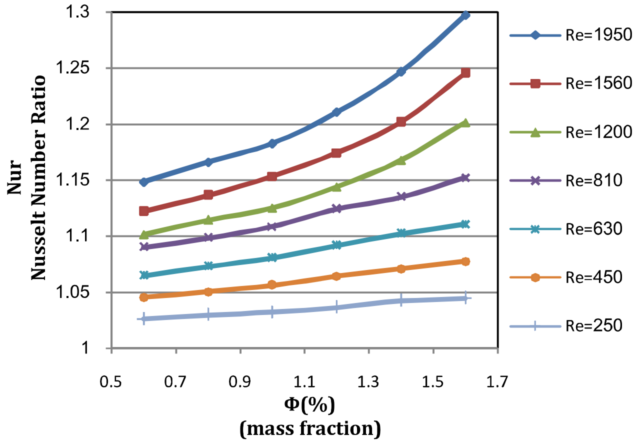

Figure 7 Plot of ratio of average Nusselt number versus concentration in different Reynolds numbers for water-Al_2O_3 nanofluid

To prepare water-TiO_2 nanofluid the same procedure of water-Al_2O_3 nanofluid is used, of course without any additives.

Figure 8 illustrates the ratio of average Nusselt number versus Reynolds number for different concentrations of water-TiO_2 nanofluid. It is observed that average Nusselt number increases with increase of both Reynolds number and concentration. The same behavior of Figure 5 is observed in Figure 8 which leads to the same explanation; the slope changes because all thermal sensors are in developing region when Reynolds number greater than 810. An increase of 22% on Nusselt number achieves using water-TiO_2 nanofluid with 1.6% concentration.

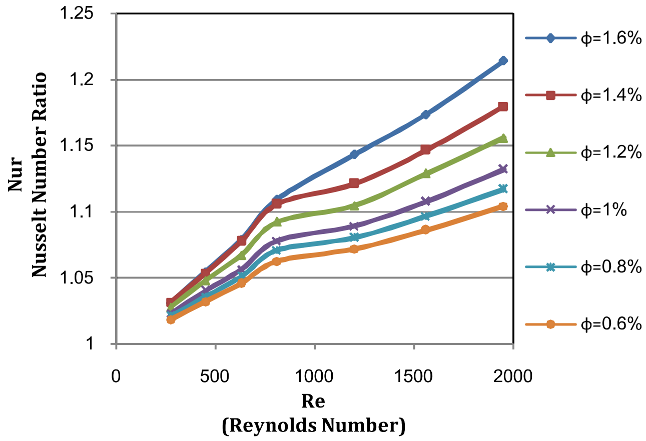

Figure 8 Plot of ratio of average Nusselt number versus Reynolds number for water-TiO_2 nanofluid in different concentrations

Figure 9 illustrates SEM image of TiO_2 nanoparticles in water for different concentrations, this image shows that some agglomeration of nanoparticles is happened.

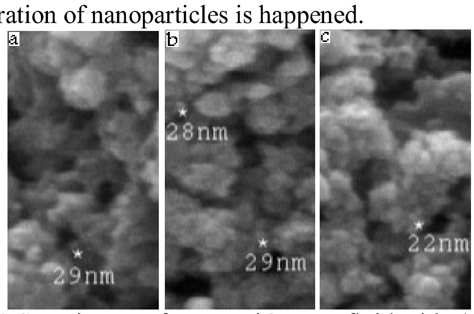

Figure 9 SEM image of water-TiO_2 nanofluid with a) 1.6% b) 0.8% c) 0.4% mass fraction

Figure 10 illustrates the ratio of average Nusselt number versus concentration for different Reynolds numbers of water-TiO_2 nanofluid. The same behaviour for this nanofluid can be observed, at lower Reynolds number, the concentration has minor effect on Nu number, while at higher Reynolds number, the concentration has major effect on Nu and it can increase it.

It's necessary to point that for preparing water-Al_2O_3 and water-TiO_2 nanofluids, nanopowders are added to water as base fluid during a long period of time. As the ultrasonic vibrator power aren't enough to prepare a stable nanofluid in high concentration, low concentrations are considered for these two nanofluids. But for water-SiO_2 nanofluid, concentrated suspension is initially used and D.I. water is added in proper amounts afterwards, to obtain nanofluid with suitable concentration. So it is possible to prepare water-SiO_2 nanofluid more concentrated than water-Al_2O_3 and water-TiO_2 nanofluids.

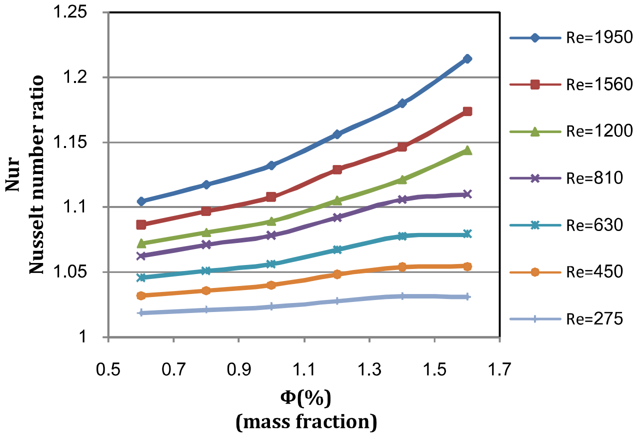

Figure 10 Plot of ratio of average Nusselt number versus concentration in different Reynolds numbers for water-TiO_2 nanofluid

Figure 11 illustrates the ratio of average Nusselt number versus Reynolds number for different concentrations of water-SiO_2 nanofluid. Entrance length effect for lower Reynolds number (less than 810) is noticeable for this kind of nanofluid. The trend of Nu number variation versus Reynolds number seems the same behaviour.

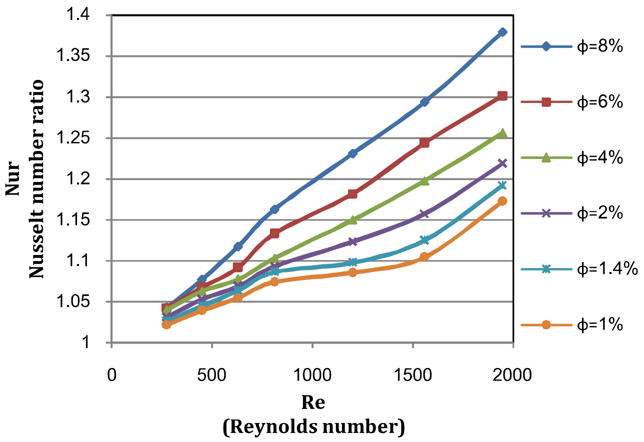

Figure 11 Plot of ratio of average Nusselt number versus Reynolds number for water-SiO_2 nanofluid in different concentrations

Figure 12 illustrates SEM image of SiO_2 nanoparticles in water for different concentrations. This image shows that the nanoparticles are well distributed in base fluid.

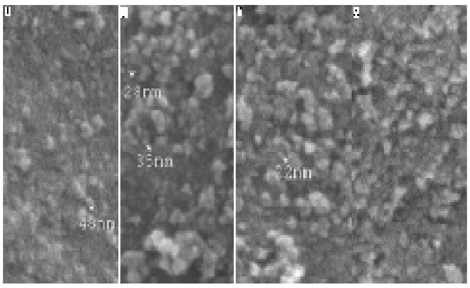

Figure 12 SEM image of water-SiO_2 nanofluid with a) 1% b) 2% c) 4% d) 8% mass fraction

Figure 13 illustrates the ratio of average Nusselt number versus concentration for different Reynolds numbers of water-SiO_2 nanofluid. The same behaviour for this nanofluid can be observed, at lower Reynolds number, the concentration has minor effect on Nu number, while at higher Reynolds number the concentration has major effect on Nu.

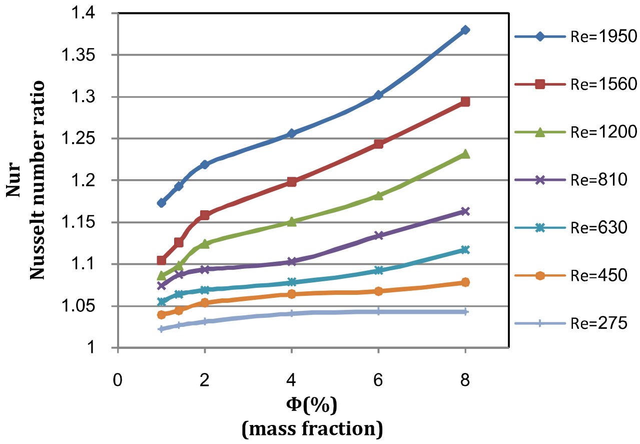

Figure 13 Plot of ratio of average Nusselt number versus concentration in different Reynolds numbers for water-SiO_2 nanofluid

After discussing on results, some correlations are obtained for average Nusselt number.

For water-Al_2O_3 nanofluid:

$$\overline{Nu} = -2 \times 10^{-8} Pe^2 + 0.001 Pe + 3.237 \qquad (8)$$

$\overline{Nu}$: Average Nusselt number, Pe: Peclet number which equals multiplication of Prandtl number (Pr) by Reynolds number (Re). Figure 14 illustrates a comparison between experimental results and the equation 8. Good agreement between obtained results and proposed correlation is evident, less than 5.93% difference in Re=1950 and Φ=1.6%.

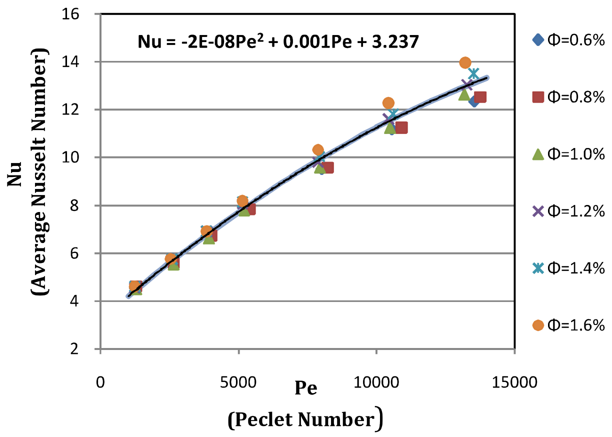

Figure 14 Comparison between experimental results and calculated results from equation (8)

For water-TiO_2 nanofluid:

$$\overline{Nu} = -1.96 \times 10^{-8} Pe^2 + 0.0009 Pe + 3.37 \qquad (9)$$

Figure 15 illustrates a comparison between experimental results and proposed equation (9) results. Maximum deviation between experimental results and those from equation (9) is 5.96% in Re=275 and Φ=1.2%.

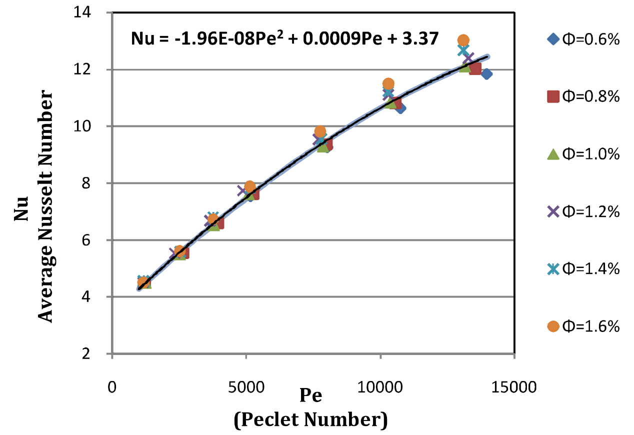

Figure 15 Comparison between experimental results and calculated results from equation (9)

For water-SiO_2 nanofluid:

$$\overline{Nu} = -10^{-8}Pe^2 + 0.0009Pe + 3.25 \quad (10)$$

Figure 16 illustrates a comparison between experimental results and recent equation. Maximum deviation between experimental results and those from equation (10) is 9.92% for Re=1950, Φ=1%.

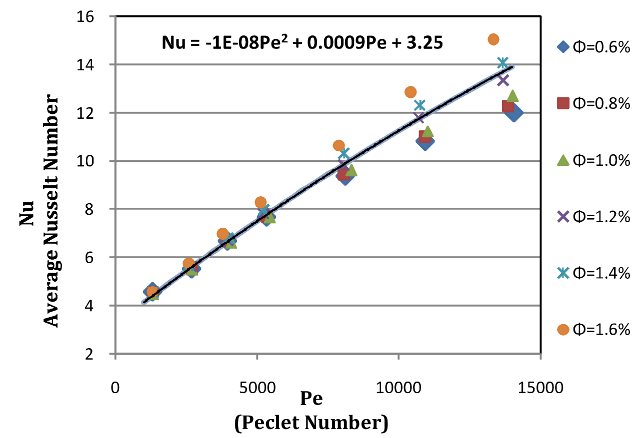

Figure 16 Comparison between experimental results and calculated results from equation (10)

CONCLUSIONS

- With increasing of Reynolds number Nur increases.
- With increasing of nanoparticles concentration Nur increases.
- With increasing of Re, slope of Nur-Φ plots increases.
- In low Re (275), slope of Nur-Φ graph is very low in all states. It means that increase of Nur doesn't vary a lot with increasing of Φ.
- Maximum increase in Nu is 37.95% which relates to water-SiO_2 nanofluid with $\Phi = 8\%\,wt$ and $Re = 1950$, and minimum increase is 1.85% which relates to water-TiO_2 nanofluid with $\Phi = 0.6\%\,wt$ and $Re = 275$.
- For three nanofluids which test have been done on, in the same concentration, increase of $\overline{Nu}$ for water-Al_2O_3 nanofluid is more than two others and for water-SiO_2 nanofluid is less than two others.

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