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Investigation of Turbulent Convective Heat Transfer and Pressure Drop of Al_2O_3/Water Nanofluid in Circular Tube

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Abstract: Turbulent heat transfer and pressure drop behavior of Al_2O_3/water nanofluid in a circular pipe with constant wall temperature was investigated experimentally where the volume fractions of nanoparticles in the base fluid were1% and 2%. Experiments were conducted in Reynolds numbers ranging from 5000 to 30000. The experimental measurements have been carried out in the fully-developed turbulent regime. The results indicated that heat transfer coefficient will increase with increase of particles concentration; this increase was about 12% for 2% particle concentration. The measurements also showed that the pressure drop of nanofluid was higher than that of the base fluid and increased with increasing the volume concentration of nanoparticles. However experimental results revealed that overall performance of nanofluid is higher than pure water. Also, experimental results proved that existing correlations can accurately estimate nanofluids convective heat transfer coefficient and friction factor in turbulent regime, provided that thermal conductivity, heat capacity and viscosity of the nanofluids are used in calculating the Reynolds, Prandtl and Nusselt numbers.

Key words: Nanofluid · Convective heat transfer · Turbulent flow · Friction factor · Overall performance

INTRODUCTION

Enhancement of the heat transfer characteristics of the thermal systems in many industries, such as energy, electronics and transportation, is a very important concern of today's world. The conventional working fluids with low thermal conductivity can no longer meet the requirements of high-intensity heat transfer. In general, the heat transfer performance of these fluids is restricted by their poor thermal properties compared to those of most solids.

The conventional methods to improve the heat transfer rate include passive techniques with application of extended or rough surfaces and swirl flow and active techniques with surface or fluid vibration and mechanical aids [1-4], However, these enhancing techniques have reached a bottleneck regarding further improvement of the heat transfer rate. So, searching for high efficiency heat transfer fluids is a challenging task of today.

Since the time nanofluids were first proposed by Choi [5] as new engineering materials, many researchers investigated the heat transfer characteristics of these novel fluids [6-9].

In general, there are two major branches in studies about the heat transfer potentials of nanofluids, nanofluids with more than 1% volumetric concentration of nanoparticles and dilute ones with less than 0.5%.

For dilute nanofluids almost all studies concluded that adding nanoparticles to base fluid will enhance heat transfer rate. Sajadi and Kazemi [10] studied turbulent convective heat transfer performance of TiO_2/water nanofluid with nanoparticles volumetric fractions less than 0.25%. They have observed that adding nanoparticles enhances heat transfer rate but there were no significant difference between results for various nanoparticles concentrations. Fotukian and Nasr [11] studied turbulent convective heat transfer performance of dilute (less than 0.24% volume) Al_2O_3/water nanofluid. In their study, increasing the volume fraction of Al_2O_3 particles in nanofluid had negligible effect on the heat transfer enhancement.

Results about nanofluids with higher concentrations are not in agreement, some researchers have reported increase in heat transfer characteristics although others have seen different behaviors.

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Pak and Cho [12] studied heat transfer behavior of Al_2O_3 and TiO_2 nanofluids up to 4% volumetric concentration, they reported that at fixed Reynolds numbers heat transfer coefficient increases with increase of nanoparticles concentration. However, they have found that the convective heat transfer coefficient of nanofluid was smaller than that of pure water when compared under the condition of constant average velocity.

Williams and Buongiorno [13] studied nanofluids with 0.9 to 3.6% volume concentration of Al_2O_3 nanoparticles. They have found that heat transfer boosts with increase of nanoparticles concentration.

Weerapun and Somchai [14] experimentally studied TiO_2/water heat transfer characteristics in the range of 0.2% to 2% volume concentration of nanoparticles. They observed that heat transfer grows by increasing nanoparticles fraction up to 1% volumetric concentration. For higher concentration, however, heat transfer coefficient growth stops and starts to decrease.

Since there is not unanimous agreement in results about heat transfer characteristics of nanofluids, this study aims at investigating the heat transfer and pressure drop of Al_2O_3water-based nanofluids flow inside the circular tubes with constant wall temperature.

Working Nanofluids: Al_2O_3 nanoparticles had 10 to 30 nm diameter which were provided from Merch Company. Nanofluids with particle volumetric concentrations of 1% and 2% was prepared and their thermo physical properties were measured at different Temperatures by Research Institute of Petroleum Industry (RIPI).Working fluids density, heat capacity, viscosity and thermal conductivity were measured within 30°C to 90°Cand are presented in Table 1 and 2 for 1% and 2% volumetric concentration of nanoparticles. The proper amount of Al_2O_3 nanoparticles were mixed with distilled water by a mixture for 30 minutes. Then, an ultrasonic homogenizer (model UP400S-Hielcher) was used to disperse nanoparticles for thirty minutes.

Table 1: Measured thermophysical properties of 1% Al_2O_3/water nanofluid

$T(K)$	$\rho(kg/m)$	$k(W/m.K)$	$\mu(N.s/m)$	$C_p(J/kg.K)$
30	1023.6	0.660	0.00102	4051.3
50	1016.2	0.691	0.00069	4053.3
70	1005.9	0.712	0.00051	4061.6
90	993.6	0.725	0.00040	4075.4

Table 2: Measured thermophysical properties of 2% Al_2O_3/water nanofluid

$T(K)$	$\rho(kg/m^3)$	$k(W/m.K)$	$\mu(N.s/m^2)$	$C_p(J/kg.K)$
30	1079.2	0.759	0.00133	3832.3
50	1071.8	0.794	0.00091	3832.3
70	1061.8	0.818	0.00067	3837.7
90	1049.8	0.833	0.00052	3847.6

Experimental Apparatus and Procedure: An experimental apparatus was built to study the flow and convective heat transfer features in a tube. As shown schematically in Fig. 1, the experimental system mainly includes a reservoir tank, a pump, a flow loop, a test section, a cooler and a steam supplier tank. The transparent plastic reservoir

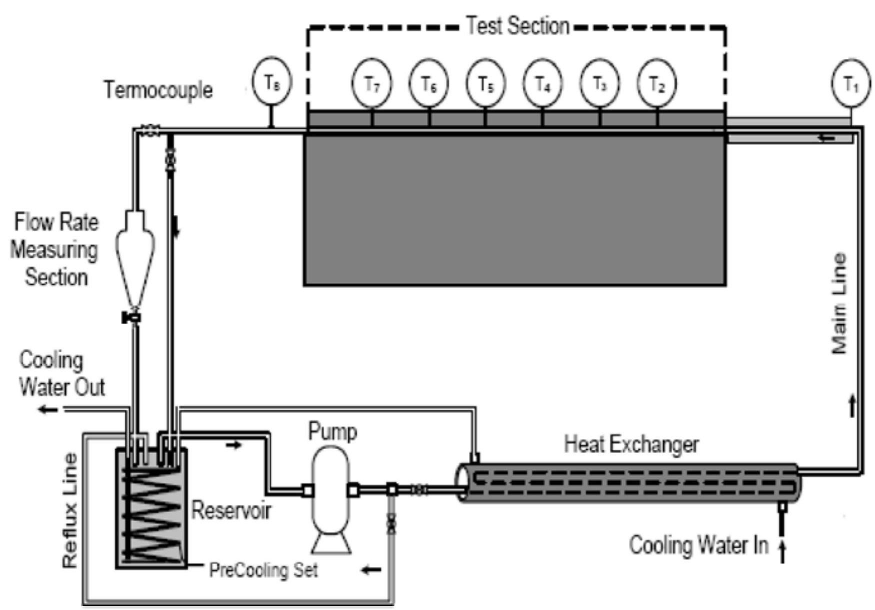

Fig. 1: Schematic diagram of experimental set-up.

tank with capacity of 6 L was manufactured to reserve the nanofluid and monitor the sedimentation rate and the height of nanofluid. The test section is a straight copper tube with the inner diameter, thickness and length of about 5, 0.675 and 1800 mm, respectively. Six K-type thermocouples were mounted on the copper tube wall at equal intervals to measure the wall temperature. Two other K-type thermocouples were inserted at the entrance and exit of the test section to measure the bulk temperature. The first 50 cm of the copper tube was thermally isolated from its beginning using fiberglass to minimize the heat loss and to guarantee hydro dynamically fully-developed condition. The flow rate was controlled with two adjusting valves, one at the end of the test section and the other at the by-pass line. The cooler includes a shell and tube heat exchanger which was used to reduce the temperature of the nanofluid at the inlet of the test section. The 50-liter steam supplier tank contains water as well as a 8KW element heater to generate fully saturated vapor. The next 120 cm of test section is surrounded by saturated vapor to reach constant wall temperature. In order to minimize the heat loss from the steam tank supplier to the surrounding area, the whole tank was thermally isolated with a fiberglass cover. A differential pressure transducer (manufactured by Endress Hauser) with an uncertainty of ±1 Pa was employed for measuring the pressure loss along the test section tube. A 1-liter glass vessel with a drain valve was utilized to calculate the flow rate. A stopwatch with accuracy of ±0.01 s was employed to measure the time required for filling the vessel.

Data Reduction: Four main parameters involved in calculating heat transfer rate of the nanofluid are heat capacity, viscosity, density and thermal conductivity, which may be quite different from those of the pure fluid. It is noteworthy that there are different correlations for predicting thermo physical properties of nanofluids, so they must be examined before putting in practice. Measured thermo physical properties were compared with common relations for nanofluids. Evaluated values with following correlations were in a good agreement (with in 9%) with measured ones, so these verified relations have been used in this study:

The effective thermal conductivity of solid-liquid mixtures could be estimated with the relation introduced by Pak and Choi.

$$K_{nf} = K_w\left(1+7.47\phi\right)$$

For the viscosity of nanofluid, existing relation which is suggested by Williams *et al.* [13] was applied:

$$\mu_{nf} = \mu_w\left(T\right)\exp\left[\frac{4.91\phi}{0.2092-\phi}\right]$$

Density and heat capacity for nanofluid are defined as follows:

$$\rho_{nf} = \phi\rho_P + (1-\phi)\rho_w$$

$$\left(\rho C_p\right)_{nf} = \left(1-\phi\right)\left(\rho C_p\right)_w + \phi\left(\rho C_p\right)$$

The rheological and physical properties of the nanofluid were calculated at the mean fluid temperature.

The experimental convective heat transfer coefficient of nanofluid is defined as follow:

$$h_{nf}\left(\exp.\right) = \frac{(\rho C_p)_{nf}\cdot A\cdot u(T_{b_{out}}-T_{b_{in}})}{\pi\cdot D\cdot L(T_w-T_b)_{LMTD}}$$

Where $(T_w - T_b)_{LMTD}$ the logarithmic is mean temperature difference and T_w is the wall temperature that is the average of six measured temperatures on tube wall at different positions. The convective heat transfer coefficient is usually expressed in the form of Nusselt number (Nu) as:

$$Nu_{nf}\left(\exp.\right) = \frac{h_{nf}(\exp.)\cdot D}{k_{nf}}$$

Where D is the tube diameter and k_{nf} is the nanofluid thermal conductivity. Traditionally, Nu is related to the Reynolds number and the Prandtl number defined as:

$$\mathrm{Re}_{nf} = \frac{uD}{\upsilon_{nf}}$$

$$\mathrm{Pr}_{nf} = \frac{\upsilon_{nf}}{\alpha_{nf}}$$

$$\alpha_{nf} = \frac{k_{nf}}{(\rho C_p)_{nf}}$$

Where ν_{nf} is the nanofluid kinematic viscosity and $á_{nf}$ is the nanofluid thermal diffusivity.

Examining the Apparatus Reliability: Before measuring the convective heat transfer coefficient and pressure drop of nanofluids, the reliability and accuracy of the experimental system was investigated using water as the working fluid.

The heat transfer results of this test were compared with the calculated values obtained from the well-known Dittus-Boelter correlation [15].

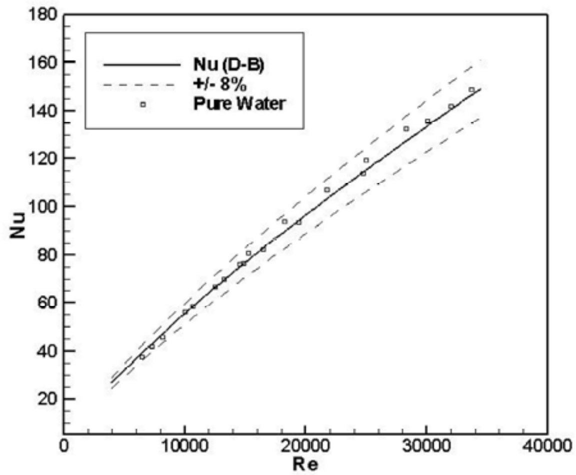

Fig. 2: Comaprison of Experimental Nusselt Number with data obtained by Dittus-Boelter corelationversus Reynolds number.

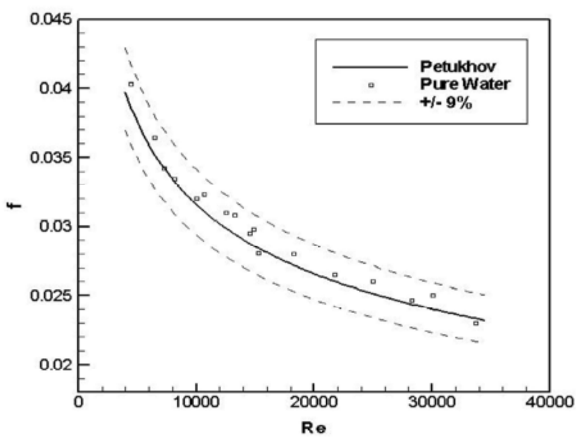

Fig. 3: Comaprison of Experimental friction factor with data obtained by Petukhov corelation versus Reynolds number.

$$Nu = 0.023\ Re^{0.8} Pr^{0.4}$$

The experimental friction factors were compared with obtained values from the Petukhov correlation [16].

$$f = (0.79\ \text{In Re} - 1.64)^{-2}$$

As can be seen in Fig. 2 and 3, coincidence between the experimental results and the calculated values for water revealed that the experimental data were in a good agreement (±9% and 8% for friction factor and heat transfer coefficient respectively) with the prediction of the correlation.

RESULTS AND DISCUSSION

Heat Transfer Results: Fig. 4 depicts Nusselt number variations versus Reynolds number for pure water and nanofluid with 1% and 2% volumetric fractions of nanoparticles. It can be seen that nanofluid heat transfer is greater than pure water and increases while the concentration of nanoparticles increases. Heat transfer coefficient amplified 6% and 13% relative to pure water for nanofluid with 1% and 2% volumetric fraction of Al_2O_3 nanoparticles respectively. These amounts of heat transfer enhancements are almost the same throughout the studied Reynolds Numbers range.

Fig. 5 and Fig. 6 compare experimental Nusselt numbers of 1% and 2% volume fraction nanofluids with the evaluated ones of Dittus-Boelter correlation using nanofluids thermo physical properties.It shows that Dittus-Boelter correlation estimates nanofluids heat transfer properly. The maximum deviation from experimental results is 7%.

Pressure Drop Results: Fig.7 presents experimental friction factors of working nanofluids and evaluated ones from Petukhov correlation. It reveals that at the same Reynolds number Petukhov correlation predicts nanofluids friction factor properly.As it can be seen in Fig. 7, nanoparticles concentration does not affect friction factor.

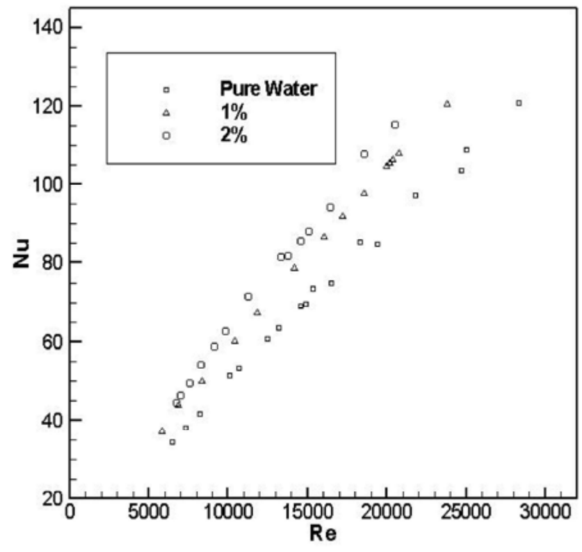

Fig. 4: Nusselt number variations versus Reynolds number for pure water and nanofluid with 1% and 2% volumetric fractions of nanoparticles

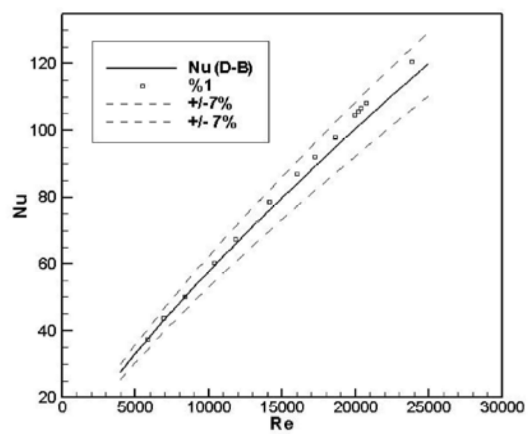

Fig. 5: Comparison of experimental Nusselt numbers of 1% volume fraction nanofluids with the evaluated ones of Dittus-Boelter correlation.

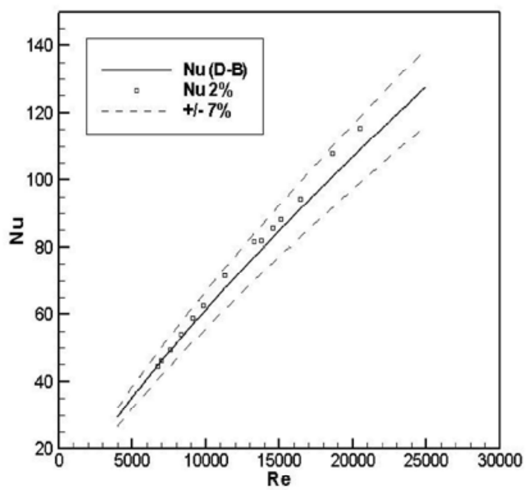

Fig. 6: Comparison of experimental Nusselt numbers of 2% volume fraction nanofluids with the evaluated ones of Dittus-Boelter correlation.

In Fig. 8 pressure drop of nanofluids is compared with that of pure water. It shows that at a given Reynolds number pressure drop of nanofluids increase significantly as nanoparticles concentration increases. For example for Reynolds number around 20000, pressure drop of nanofluids are 40% and 110% higher than pure water for 1% and 2% volume fractions of nanoparticles respectively.

Overall Performance of Nanofluids: It has been observed that heat transfer and pressure drop both increase when the nanoparticles concentration increase. It is obvious these two parameters contradict each other. In order for better comparison of nanofluids heat transfer behavior the overall performance of nanofluids defined as the ratio of

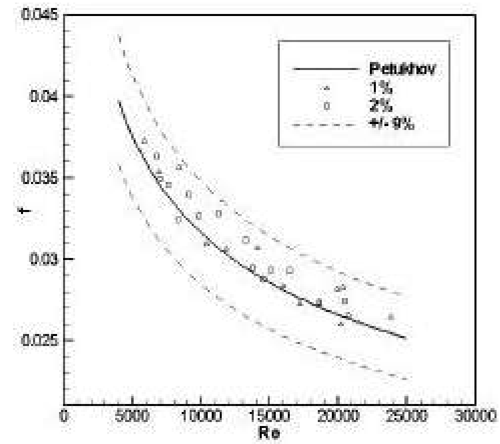

Fig. 7: Comparison of experimental friction factors of working nanofluids and evaluated ones from Petukhov correlation.

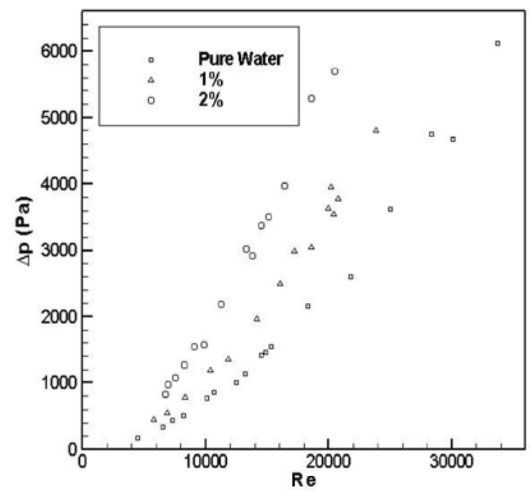

Fig. 8: Pressure drop of nanofluids and pure water versus Reynolds Number

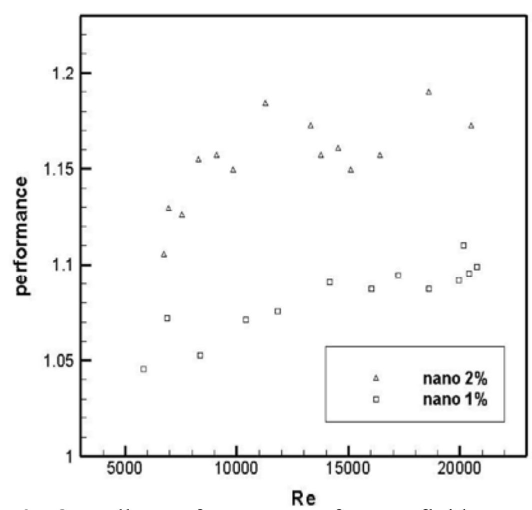

Fig. 9: Overall performance of nanofluids versus Reynolds Number

Nusselt number for the nanofluid to that of pure water for equal pumping power.

$$\eta = \left.\frac{Nu_{nf}}{Nu_w}\right|_{epp} = \frac{Nu_{nf} / Nu_w}{\left(f_{nf}/f_w\right)^{1/3}}$$

Fig. 9 shows the variation of the overall performance with Reynolds numbers for 1% and 2% volume fraction of nanoparticles. It can be seen that increase in nanoparticles concentration increases overall performance of fluids. Furthermore it has a slight growth as Reynolds number grows.

CONCLUSION

The following conclusions have been drawn from the presentstudy:

- By suspending Al_2O_3 nanoparticles within 1% and 2% volumetric concentrations range, heat transfer coefficient of nanofluids increased. For1% volume fraction of Al_2O_3, an increase of about 12% in theheat transfer coefficient was occurred in comparison with purewater. In case of 2% volume fraction of Al_2O_3particles, heat transfer enhancement was about 19%. These amounts of heat transfer enhancements are almost the same throughout the studied Reynolds Numbers range.
- Common correlations for heat transfer coefficient and friction factor of pure fluids are applicable for nanofluids when nanofluids thermo physical properties are used in correlations. Dittus-Boelter correlation estimates nanofluid Nusselt number with maximum deviation of 6% from experimental results. Petukhov correlation also predicts friction factor of nanofluids properly (with maximum deviation of 5%).
- Nanoparticles concentration does not affect friction factor.
- Pressure drophowever will leap by adding Al_2O_3 nanoparticles to water. More nanoparticles concentration results into higher pressure drop.
- Suspending Al_2O_3nanoparticles in the base fluid increases its overall performance. Higher nanoparticles concentration results more overall performance. Overall performance has slight growth while Reynolds numbers are increasing.

Nomenclature:

A	tube cross section area, m^2
C_p	specific heat capacity, KJ/KgK
D	diameter of the tube, m
h	heat transfer coefficient, W/m^2K
k	thermal conductivity, W/mK
L	length of the tube, m
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
T	temperature, K
u	mean fluid velocity, m^2/s

Greek Symbols:

α	thermal diffusivity, m^2/s
μ	viscosity, Pa s
ρ	density, Kg/m^3
υ	kinematics viscosity, m^2/s
ϕ	nanoparticle volume fraction

Subscripts:

b	bulk
nf	nanofluid
w	water
p	solid nanoparticle
exp.	obtained experimentally
v	laminar sublayer
in	inlet
out	Outlet

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