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CONVECTIVE HEAT TRANSFER OF TITANIUM (IV) OXIDE NANOFLUIDS UNDER TURBULENT FLOW CONDITION

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ABSTRACT

This study has experimentally investigated the flow behavior and convective heat transfer coefficient of TiO_2/distilled water nanofluids flowing inside a horizontal circular tube at turbulent regime under a uniform heat flux boundary condition. Anatase titanium (IV) oxide nanoparticles of average size approximately 21 nm dispersed into distilled water with volume fraction range from 0.1 to 0.5 vol.% were used as nanofluids. The observed nanofluids were assumed as time-independent non-Newtonian fluid with their specific values of power law index and consistency coefficient. A new correlation involving the microconvection and microdiffusion effects was proposed to predict Nusselt number. As nanofluid samples behave the non-Newtonian fluid, the drag reduction phenomenon should be theoretically exhibited in turbulent flow regime. This drag reduction phenomenon might be one of the important factors that was responsible on the improvement of heat transfer performance in nanofluids aside from the established heat transfer enhancement mechanisms.

Keywords:titania, nanofluids, non-Newtonian, convective heat transfer, drag reduction.

INTRODUCTION

The term nanofluid, firstly introduced by Choi [1], was a novel concept by dispersing nanometer-sized solid particles smaller than 100 nm into the conventional heat transfer fluids (HTFs) such as, water, ethylene glycol, and engine oil as a base fluid. The enhanced thermal conductivity constituted an initial promise for nanofluids as advanced HTFs. The inherently poor thermal conductivity of conventional HTFs has restricted the heat transfer enhancement in thermal system. Numerous experimental or theoretical studies have been performed to predict thermal conductivity augmentation [2-12]. For nanofluids with metallic oxide dispersed into ethylene glycol, Xie, *et al.* [13] reported that the thermal conductivity increases nonlinearly with increasing in particles concentration and viscosity of nanofluids exhibits Newtonian rheological behavior. Moreover, it was important to evaluate the thermal conductivity and viscosity based on rheological behavior which provides structural information for the thermal conductivity prediction and flow properties of nanofluids [14-17]. In spite of the many thermal conductivity models, the heat transfer enhancement was a better indicator than thermal conductivity enhancement for nanofluids in thermal system design [18]. Several studies on nanofluids convective heat transfer have been reported in the previous literatures with using different approach [19-23]. Convective heat transfer coefficient depends not only on thermal conductivity but also on other thermophysical properties, such as density, viscosity, and heat specific [24]. However, the several additional factors such as, Brownian force, gravity, Brownian diffusion, drag on particle, sedimentation, and dispersion were necessary to be considered in nanofluids convection [21]. However, Ding, *et al.* [25] suggested that the competing influence of particle migration on thermal boundary layer thickness and that on thermal conductivity might be responsible for convective heat transfer enhancement.

Assumption in dispersion of the suspended nanoparticles has been used in the convective heat transfer enhancement study by previous researchers. Xuan and Li [22] proposed that intensification of turbulence due to the presence of nanoparticles can induce the heat transfer enhancement. The traditional correlations for predicting friction factor of base fluid can be used to calculate turbulent friction factors of the observed nanofluids at the average viscosity [20,22]. However, Buongiorno [19] reported that particle dispersion effect is highly small and thus cannot clarify the convective heat transfer augmentation. Moreover, turbulence was not influenced by the nanoparticles presence. Until now, there are three types in convective heat transport model for nanofluids namely, homogeneous flow model [1; 26], dispersion model [21], and two-component non-homogeneous equilibrium model [19]. It was very important to involve rheological behavior of nanofluids. The rheological properties affected on the convective heat transfer, pressure drop and hence the pumping power when nanofluids were circulated in a closed loop of heat transfer in thermal system [27; 28]. There is an controversy on rheological flow behavior of nanofluids that is interesting to be discussed. Very few studies have been reported on the rheological properties related to the convective heat transfer in the previous literature. The effect of nanofluids rheological behavior on natural convection heat transfer has been numerically studied for both Newtonian and non-Newtonian model [29]. However, there has been found the inconsistency results in their studies [30-32].

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He, *et al.* [32] studied experimentally on the rheological measurement and heat transfer behavior of TiO_2/water nanofluids with particles concentration of 0.24, 0.60, and 1.18 vol.%. The measured data of the nanofluids sample flowing through a vertical circular tube were performed under a constant heat flux condition at both laminar and turbulent flow. The shear viscosity decreased with increasing in volume fraction and decreasing in agglomerates. This flow behavior showed the thinning behavior at the shear rate lower than 100 s^{-1}. In turbulent flow, the convective heat transfer coefficient increased with increasing in particles concentration at the given Reynolds number and particles size. Hojjat, *et al.* [33] investigated TiO_2 nanoparticles (≈10 nm) with particles concentration range between 0.1 and 1.5 vol.% in an aqueous solution of carboxymethyl cellulose (CMC) flowing through a uniform heat flux condition under turbulent flow. The base fluid and titania nanofluids showed shear-thinning rheological behavior. Average heat transfer enhancement increased with an increase in volume fraction and it was larger than that of the base fluid. Kayhani, *et al.* [34] carried out an experimental investigation on TiO_2/water nanofluids flowing through a horizontal circular tube under a uniform heat flux at turbulent flow. The spherical titania nanoparticles (≈15 nm) were dispersed into water with particles concentration range from 0.1 to 2.0 vol.%. Their results concluded that the addition of titania nanoparticles played a conclusive role for improving the heat transfer characteristics of nanofluids in turbulent flow. In turbulent flow, however, a dramatic heat transfer enhancement did not occur with increase in titania nanoparticles concentration. In turbulent flow, spherical nanoparticles with 45 nm in nominal diameter of aluminum oxide ultrafine powder dispersed into water have been also studied by Vishwanadula and Nsofor [35].

This present study would focus on the experimental investigation of convective heat transfer of the anatase titanium (IV) oxide nanofluids in turbulent flow. Under a uniformly heated horizontal circular tube condition, the flow behavior and convective heat transfer coefficient of TiO_2/distilled water nanofluids were studied in this work. The observed nanofluid was assumed as a time-independent non-Newtonian fluid which has a specific value of power law parameter. Therefore, shear flow dependent was involved to evaluate the flow and heat transfer behaviors. The purposes of this work were to characterize rheological flow behavior and to evaluate convective heat transfer of non-Newtonian TiO_2/distilled water nanofluids. The anatase titania nanoparticle concentrations used in this work were 0.1, 0.3, and 0.5 vol.%.

EXPERIMENTAL SETUP AND PROCEDURE

Titanium (IV) oxide nanoparticles used in this work were procured from Sigma-Aldrich (USA). According to a detailed characterization of titania nanoparticles in our previous work [36], it can be seen that the transmission electron microscopy (TEM) photograph and the X-ray diffraction (XRD) spectra measurements show spherical particles morphology and anatase structure, respectively. By using the two-step method, titania nanoparticles were dispersed into distilled water with various particle concentrations of 0.1, 0.3, and 0.5 vol.%. The experimental setup used in this work, a horizontal flow-loop apparatus, was shown schematically in Figure-1. It comprised a test section, a magnetic gear pump, a reservoir, and measurement devices. A test section was constructed from a stainless steel circular tube with 4.25 mm in inner diameter and 1260 mm in the distance between the high and low pressure taps. A uniformly heated tube of the test section was generated by the variac transformer (OKI $TDGC_2$-3000) connected to nichrome coils (Ni 30%, Cr 20%). The test section was thermally isolated by wrapping the outer surface to minimize heat loss to the surrounding. A magnetic micro gear pump (WT3000-1JB, Baoding Longer Precision Pump) was used to circulate the observed nanofluids through the test section. To ensure hydrodynamically fully developed turbulent flow, nanofluids should previously flow through a calming section. Volumetric flow rates were controlled gradually by adjusting the rotation speed of the magnetic gear pump in the range from 300 to 2000 rpm. Nanofluids flow rate was measured by collecting in the given period of time and it was weighed carefully in an accurate mass balance. A handheld digital manometer (Dwyer model 490-2) was used to measure the pressured drop at the fixed taps. To keep a constant inlet temperature, a chiller (CL-280 Resun) was used in this experiment with 280 W in the refrigerating capacity. Data acquisition module (ADAM 4018+ and ADAM 4561) connected to a PC was used to record the obtained temperature data from the eight K-type thermocouples.

The thermophysical properties of titania nanofluid depend not only on the properties of distilled water and titania nanoparticles but also particle concentration. In this work, the density (ρ_{nf}) and specific heat capacity ($c_{p,nf}$) of the observed nanofluid are determined by the mixture formula whereas the thermal conductivity was computed by the previous empirical correlation.

$$\rho_{nf}(T) = \phi\rho_{np} + (1-\phi)\rho_{bf}(T) \quad (1)$$

$$c_{p,nf} = \frac{(1-\phi)(\rho c_p)_{bf} + \phi(\rho c_p)_{np}}{(1-\phi)\rho_{bf} + \phi\rho_{np}} \quad (2)$$

Where, *nf*, *bf* and *np* are the subscribt of nanofluids, base fluid and nanoparticles, respectively. A symbol ϕ points volume fraction. To predict the effective thermal conductivity, the general correlation of effective thermal conductivity was defined by previous study [37].

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$$k_{nf}\left(T\right)=k_{bf}\left(T\right)\cdot\left(a+b\phi\right) \quad (3)$$

The constant values are obtained by extrapolating experimental data with temperature ranging from 15 to 35°C. In this work, the constant values in Equation (3) are 1.0191 and 0.0352 for *a* and *b* constants, respectively.

FLOW BEHAVIOR OF NON-NEWTONIAN NANOFLUIDS

As mentioned above, nanofluids that are prepared by dispersing anatase titania nanoparticles into distilled water with various particle concentrations are assumed as time-independent non-Newtonian fluids in this work. Therefore, the apparent viscosity depends only on the shear rate at any particular moment. For non-Newtonian fluids approach, the relationship between shear stress and shear rate is more complex. It can be rheologically modeled as a power law fluid expressed as follows:

$$\tau = K\,\dot{\gamma}^{n} \quad (4)$$

For flow of general time-independent non-Newtonian fluids, the nominal shear rate can be determined the following correlation.

$$\dot{\gamma}=\left.\frac{du}{dr}\right|_{r=R} \quad (5)$$

Or,

$$\dot{\gamma}=\frac{8\overline{u}}{D} \quad (6)$$

Using the force balance on an element of Newtonian fluid along *L* length, the wall shear stress can be obtained by calculating this equation.

$$\tau_{w}=\frac{\Delta P}{4L/D} \quad (7)$$

For Newtonian fluids, a plot of shear stress (τ_w) versus shear rate ($\dot{\gamma}$) on Cartesian coordinate is a straight line having a slope equal to dynamic viscosity (μ). The term viscosity has no meaning for non-Newtonian fluid unless it is related to a particular shear rate called as the apparent viscosity. It can be defined as follows:

$$\eta_{a}=\frac{\tau_{w}}{\dot{\gamma}} \quad (8)$$

The power law model introduces flow behavior index (n) defined as the slope of log-log plot of shear stress at the tube wall versus flow characteristics ($8\overline{u}/D$) at any point along the test section.

$$n=\frac{d\ln\left(\dfrac{\Delta P}{4L/D}\right)}{d\ln\left(\dfrac{8\overline{u}}{D}\right)} \quad (9)$$

Therefore, the wall shear stress can be derived from non-Newtonian fluid flow behavior defined as follows:

$$\tau_{w}=K'\left(\frac{8\overline{u}}{D}\right)^{n} \qquad K'=K\left(\frac{3n+1}{4n}\right)^{n} \quad (10)$$

Metzner and Reed correlation introduced the generalized Reynolds number for fully developed laminar flow inside a circular tube with considering the power law index and consistency coefficient [38].

$$\mathrm{Re}_{g}=\frac{\rho_{nf}\overline{u}^{2-n}D^{n}}{K'8^{n-1}} \quad (11)$$

For turbulent flow of general time independent non-Newtonian fluids in smooth cylindrical tube, Fanning friction factor can be calculated from Dodge and Metzner correlation [39].

$$\frac{1}{\sqrt{f_{F,tturb}}}=\frac{4.0}{n^{0.75}}\cdot\log_{10}\left[\mathrm{Re}_{g}\left(f_{F,turb}\right)^{(1-n/2)}\right]-\frac{0.4}{n^{1.2}} \quad (12)$$

It should be noted that the Darcy friction factor is four times of the Fanning friction factor.

By using a horizontal pipe viscometer, the power law parameters can be determined. In our previous work, the apparent viscosity of the observed nanofluids decreased with an increase in gradient velocity. This indicates that anatase titania nanoparticles dispersed into distilled water are non-Newtonian fluid. They behave shear-thinning or pseudoplastics behavior. The values of power law index for the observed nanofluids were n ≈ 0.82–0.95.

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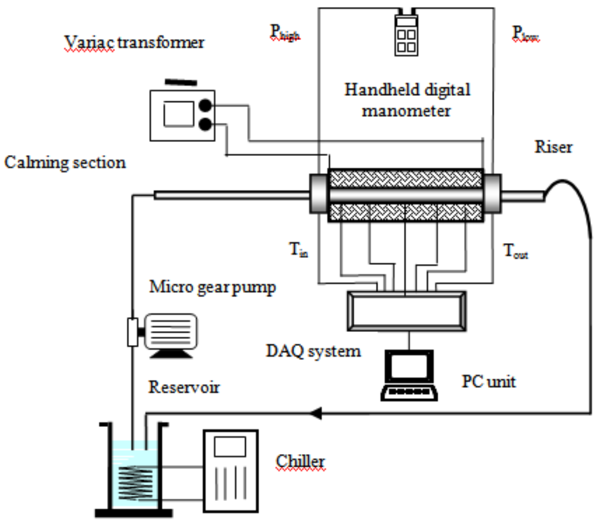

Figure-1. Schematic diagram of the experimental setup used in this work.

RESULTS AND DISCUSSIONS

In this work, anatase titanium (IV) oxide nanoparticles dispersed into distilled water with particle concentrations of 0.1, 0.3, and 0.5 vol.% were used to investigate convective heat transfer and hydrodynamic characteristics of nanofluids. Reynolds number was varied from 3000 to 10,000 and the inlet temperature of nanofluids was maintained constant by means of a chiller cooling system.

Prior to conducting experiments in heat transfer performance, the validation of experimental setup was performed to ensure its reliability and accuracy. For thermally fully developed turbulent flow regime ($L_{t,turbulent} \approx 10\ D$), the measured Nusselt number for pure water at the test section was compared with those of obtained from the established correlation, that is, the Gnielinski and Pethukov equation which was defined as follows:

Gnielinski equation

$$Nu = \frac{(f/8)(\mathrm{Re}-1000)\mathrm{Pr}}{1.0+12.7(f/8)^{0.5}\left(\mathrm{Pr}^{2/3}-1\right)} \quad (13)$$

Pethukov equation

$$Nu = \frac{(f/8)\mathrm{Re}\cdot\mathrm{Pr}}{1.07+12.7(f/8)^{0.5}\left(\mathrm{Pr}^{2/3}-1\right)} \quad (14)$$

The Darcy friction factor can be determined from the well-known Colebrook equation as follows:

$$\frac{1}{f} = -2.0\log\left(\frac{\varepsilon/D}{3.7}+\frac{2.51}{\mathrm{Re}\sqrt{f}}\right) \quad (15)$$

Where, ε/D is the relative roughness. The symbol of ε represents an equivalent roughness value in which its value is 0.002 for stainless steel tube.

As shown in Figure-2, the measured Nusselt numbers have an excellent agreement with Pethukov equation for distilled water. However, the Nusselt number values obtained from Gnielinski equation show slightly lower compared to for both the measured data and that calculated from Pethukov equation.

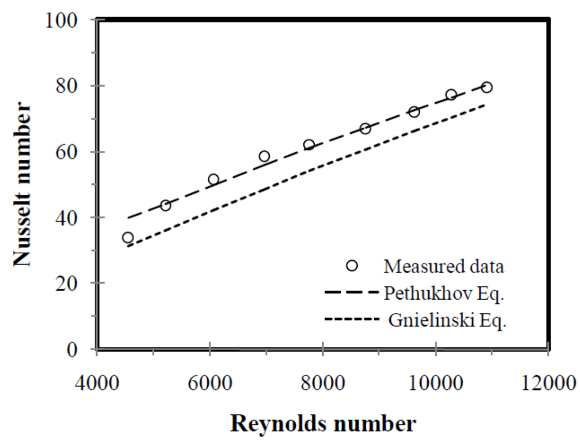

Figure-2. Validation data of Nusselt number between the measured data and the established correlation for distilled water.

So far, there are two empirical equations to predict Nusselt number for titania nanofluids at turbulent flow, specifically Pak and Cho [20] and Duangthongsuk and Wongwises correlations [23]. On the other hand, Xuan and Li [22] also proposed a new correlation for nanofluids at turbulent flow but their equation only applied for copper (Cu) nanoparticles. In this work, those empirical correlations were used for comparison with the experimental results. The measured Nusselt number of TiO_2/water nanofluids used in this work was evaluated based on non-Newtonian fluid with using the generalized Reynolds number whereas the established correlations were computed by using Newtonian fluid approach. A detailed explanation would be revealed to clarify the controversial result in convective heat transfer performance as reported by the previous researchers.

Figure-3 shows the comparison between the measured Nusselt number and that of obtained from Pak and Cho equation. Under the constant average velocity condition, Pak and Cho [20] investigated turbulent convective heat transfer behaviors in a circular tube of ultrafine metallic oxide particles suspended in water

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namely, γ-alumina (Al_2O_3) and titanium dioxide (TiO_2) with mean diameters of 13 and 27 nm, respectively. A modified Dittus-Boelter equation for predicting Nusselt number was proposed in their work as follows:

$$Nu_{nf} = 0.021\mathrm{Re}_{nf}^{0.8}\,\mathrm{Pr}_{nf}^{0.5} \quad (16)$$

Equation (16) can be used for a fraction volume below 10 vol.%. The Reynolds number and Prandtl number were varied in the ranges of 10^4–10^5 and 6.5–12.3, respectively.

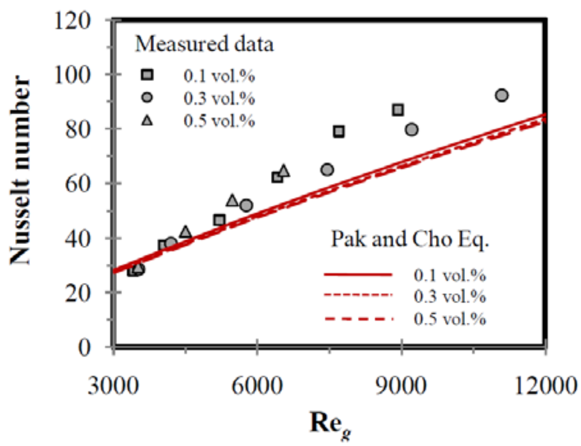

Figure-3. Comparison of TiO_2/distilled water nanofluids between the measured data and Pak and Cho correlation.

As shown in Figure-3, it is seen that Pak and Cho correlation fails to predict the Nusselt number of this experimental data. The measured Nusselt numbers are higher than those of Pak and Cho equation. On the other hand, an anomalous result of convective heat transfer enhancement in turbulent flow has been also reported by them in which heat transfer coefficient at volume fraction of 0.3 vol.% Al_2O_3 and TiO_2 nanoparticles was found 12% smaller than that of pure water. This might be caused by their correlation without considering the effect of particle concentration and by different configuration of the experimental setup. As expressed in Equation (16), it is clearly seen that volume fraction is not involved in their equation.

To get better accuracy for predicting Nusselt number of nanofluids, Duangthongsuk and Wongwises [23] modified Pak and Cho correlation with involving the effect of particles concentration. They have investigated on the heat transfer performance for TiO_2/water nanofluids (~21 nm) flowing through turbulent flow regime in a horizontal counter flow type heat exchanger with particle concentrations of 0.2–0.5 vol.%. For predicting heat transfer performance of titania nanofluids, a new correlation was proposed.

$$Nu_{nf} = 0.074\mathrm{Re}_{nf}^{0.707}\,\mathrm{Pr}_{nf}^{0.385}\,\phi^{0.074} \quad (17)$$

Equation (17) can be used for a fraction volume of ≤ 1.0 vol.% and a Reynolds number range from 3000 to 18,000. With involving particles concentration, the measured data in this work are closer to the results of the Nusselt numbers calculated from Duangthongsuk and Wongwises correlation than the values obtained from Pak and Cho equation as shown in Figure-4. However, the measured Nusselt numbers show slightly under-predicted at Reynolds numbers below 4000. Transition flow regime of nanofluids might still occur at this Reynolds number.

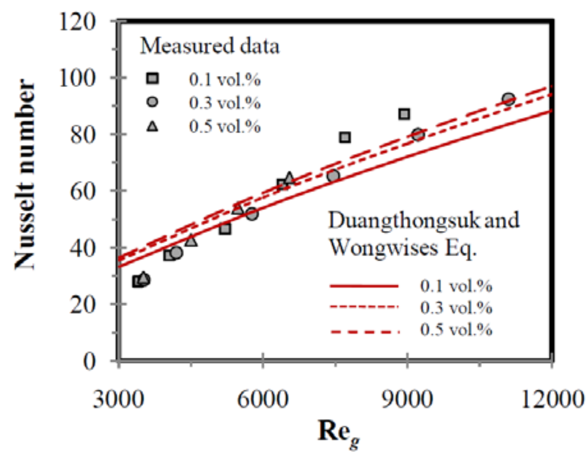

Figure-4. Comparison of TiO_2/distilled water nanofluids between the measured data and Duangthongsuk and Wongwises equation.

Finally, a new heat transfer relationship for predicting Nusselt number of nanofluids proposed by Xuan and Li [22] was compared with the experimental result in this work. They assumed that nanofluids can be approached as single-phase flow with considering the microconvection and microdiffusion effects of the dispersed nanoparticles. A new type for the turbulent heat transfer was proposed in their investigation as follows:

$$Nu_{nf} = 0.0059\left(1.0 + 7.6286\phi^{0.6886} Pe_d^{0.001}\right)\mathrm{Re}_{nf}^{0.9238}\,\mathrm{Pr}_{nf}^{0.4} \quad (18)$$

Where, Pe_d is the Peclet number of nanoparticle $= u_p d_p / \alpha_p$, α_p is thermal diffusivity of nanoparticles. This equation can be applied for pure copper particles (≈100 nm) dispersed into deionized water flowing through a circular tube at volume fraction range from 0.3 to 2.0 vol.%. The Reynolds numbers were varied in the range from 10,000 to 25,000.

Comparison between the measured Nusselt number and the calculated data from Xuan and Li correlation are demonstrated in Figure-5. It is seen that the

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Nusselt number obtained from this correlation have the very high values compared with those of the measured data. A dramatic enhancement of the observed nanofluids was as much as 40% at the same velocity. This revealed that the calculated convective heat transfer coefficient from Xuan and Li equation contradicts with that of the Pak and Cho correlation. In addition to volume fraction, this anomaly might be caused by particle dimension, material properties, and proper design of the nanofluid samples. As reported several previous researcher, metal-based nanofluids have higher heat transfer coefficient that those of metal oxide-based nanofluids.

In this present work, microconvection represented by Peclet number and parameter power law expressed by the generalized Reynolds number were considered to establish the empirical correlation. In addition to those non-dimensional numbers, volume fraction and Prandtl number were also involved as independent variables for predicting Nusselt number. The empirical correlation in this work was adopted from the light of analysis and derivation reported by Xuan and Roetzel [21]. The following relationship was proposed to correlate the measured data for titania nanofluids at turbulent flow regime.

$$Nu_{nf} = c_1\left(1.0 + c_2\phi^{m_1} Pe_d^{m_2}\right)\mathrm{Re}_g^{m_3}\,\mathrm{Pr}_{nf}^{0.4} \quad (19)$$

Those constants in Equation (19) are determined by non-linear regression (SOLVER) with using iteration, tolerance, and convergence of 10,000, 5%, and 0.0001, respectively. Analysis result of the correlation constants is listed in Table-1.

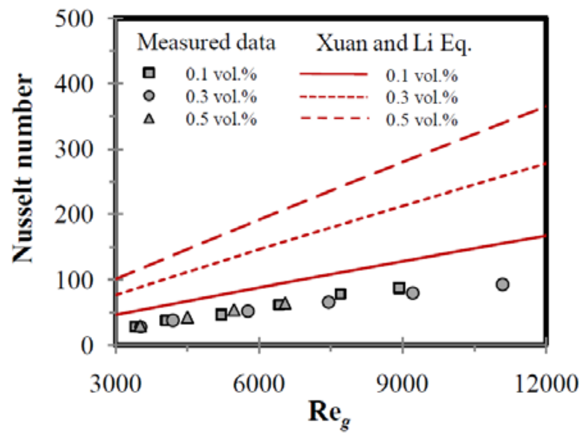

Figure-5. Comparison of between the measured data for TiO_2/distilled water nanofluids and the Xuan and Li correlation for Cu/deionized water.

Comparison between the empirical correlation obtained from Equation (19) and the experimental data of Nusselt number is shown in Figure-6. The scatter results of Nusselt number values show a good conformity between the measured data and the calculated result by the above empirical correlation in the Reynolds number range from 6000 to 12,000. This might be caused by nanofluids treatment in heat transfer evaluation, and by boundary condition of the test section. In the existing correlations, nanofluids were treated as Newtonian fluid with viscosity constant at the given temperature and the shear-dependent of viscosity was not considered in their correlation.

Table-1. Constant values of the empirical correlation.

Nanofluids	Constant values					
	c_1	c_2	m_1	m_2	m_3	R^2
TiO_2/distilled water	2.59E-03	1.339	0.203	0.509	1.031	1.0

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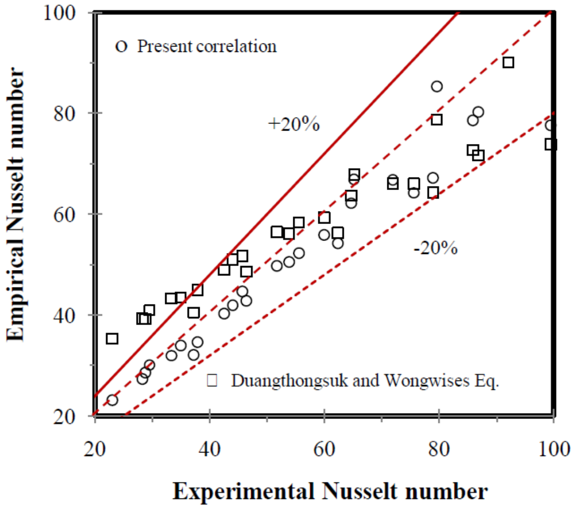

Figure-6. Comparison of Nusselt number between the empirical correlation and experimental data for TiO_2/distilled water nanofluids.

In addition to the convective heat transfer investigation, it is necessary to observe the flow behavior of nanofluids as non-Newtonian fluids for practical application. To ensure the validity and accuracy of friction factor measurement, distilled water was used to test reliability of the experimental setup. It is noted that distilled water behaves as Newtonian fluid. The well-known Hagen-Poiseuille and Blasius correlation was used to validate the Darcy friction factor in laminar and turbulent flow regime, respectively, as follows.

Hagen-Poiseuille equation

$$f = \frac{64}{\mathrm{Re}} \quad (20)$$

Blasius equation

$$f = 0.3164\,\mathrm{Re}^{-0.25} \quad (21)$$

The test section length used in this work has complied hydrodynamically fully developed flow for both laminar ($L_{h,laminar} \approx 0.05\ ReD$) and turbulent region ($L_{h,turbulent} \approx 10\ D$). The measured data of friction factor can be calculated from the Darcy–Weisbach equation as follows:

$$f = \frac{D}{L}\frac{\Delta P}{(1/2)\rho\bar{u}^2} \quad (22)$$

As shown in Figure-7, the experimental data of friction factor flowing through a circular tube have an excellent agreement with those of the calculated values from Hagen-Poiseuille and Blasius equation for laminar and turbulent flow, respectively. It can be stated that the experimental setup used in this work is valid and accurate.

The obtained Fanning friction factor of titania nanofluids in a circular tube was shown in Figure-8. The measured data were compared with the classical equations, namely the Hagen-Poiseuille equation and Blasius equation for laminar and turbulent flow, respectively. It can be seen that friction factor reduces in turbulent flow regime. This friction factor reduction at turbulent flow is called as the drag reduction phenomenon. The maximum friction factor reduction can be calculated by Virk's asymptote for any non-Newtonian expressed as follows:

$$\frac{1}{\sqrt{f}} = 19.0\log\left(\mathrm{Re}\sqrt{f}\right) - 32.4 \quad (23)$$

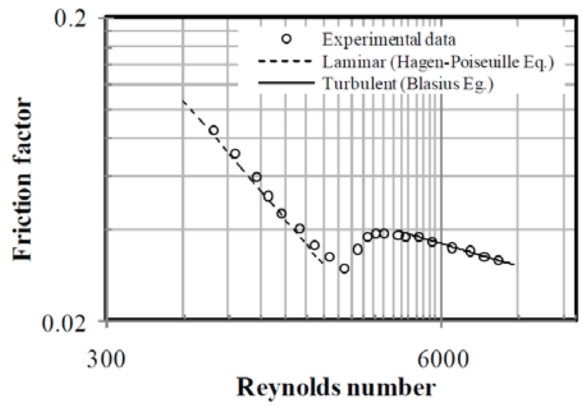

Figure-7. Validity result of friction factor for distilled water.

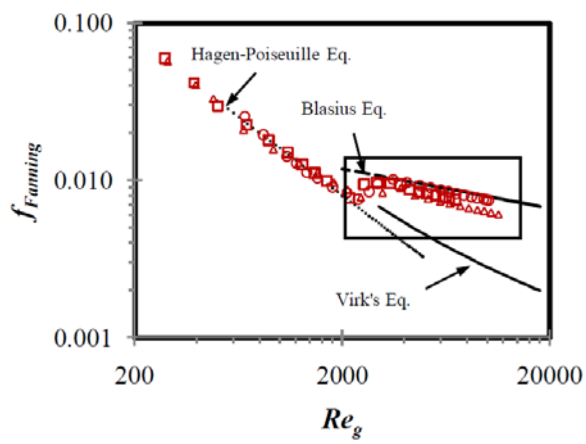

Figure-8. Drag reduction phenomenon of non-Newtonian nanofluids in turbulent flow.

Theoretically, the drag reduction should indeed occur if nanofluids are assumed as non-Newtonian fluid. Friction factors of non-Newtonian fluids in turbulent flow

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regime reduced with a decrease in the power law index lower than 1.0 or Newtonian fluid whereas the same friction factors were shown in laminar flow [40]. The drag reduction was a flow phenomenon in which the pressure drop or frictional drag in turbulent tube flow reduces due to addition of the additives such as, polymers, surfactants and fibres [41]. Nanoparticles dispersed into base fluid can serve as an additive in nanofluids flow in this case. In addition to the key mechanisms reviewed by Chandrasekar, *et al.* [42], this phenomenon might be one of mechanism factors that is responsible on the heat transfer enhancement of non-Newtonian nanofluids. In this work, the convective heat transfer enhancement in turbulent flow due to drag reduction agrees well with the hypothesis of the key mechanism proposed by Xuan and Li [22] in respect to drag on particle.

Figure-9 shows the comparison of friction factor between the measured data and the established correlation in turbulent flow. Dodge and Metzner correlation as expressed in Equation (12) was used to predict turbulent flow of non-Newtonian nanofluids. As shown this figure, it is seen that the measured data are lower than the values calculated from the classical Blasius equation. Duangthongsuk and Wongwises correlation for predicting the friction factor of TiO_2/water nanofluids also showed the same phenomenon although they are assumed as Newtonian fluid. It is noted that their correlation considers the effect of particles concentration on friction factor expressed as follows:

$$f = 0.961\phi^{0.052}\,\mathrm{Re}^{-0.375} \quad (24)$$

Equation (24) fails to predict the measured friction factor in this experiment. By assuming as non-Newtonian fluid in this work, the obtained friction factors from Equation (12) are lower than those of the correlation proposed by Duangthongsuk and Wongwises [23].

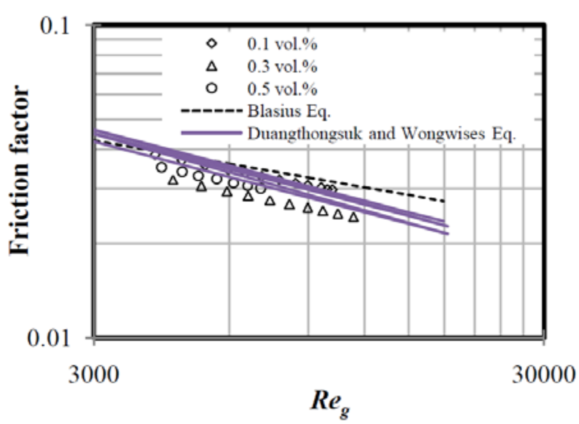

Figure-9. Comparison of friction factor between the measured data for non-Newtonian nanofluids and the established correlation for Newtonian nanofluids.

CONCLUSIONS

The flow behavior and convective heat transfer performance of TiO_2/distilled water nanofluids flowing through in a horizontal circular tube under turbulent regime have been experimentally studied. The observed nanofluids were assumed as time-independent non-Newtonian fluid with their specific values of power law index and consistency coefficient. The influence of volume fraction and mass flow rate on flow behavior and heat transfer characteristic of nanofluids were evaluated in this work. The results showed that the Pak and Cho correlation and Xuan and Li relation fail to predict the Nusselt number. The calculated Nusselt number from the Pak and Cho equation was lower and the Xuan and Li correlation was higher than those of this present experiment, respectively. A good agreement of the results was shown by Duangthongsuk and Wongwises correlation with considering the effect of particles concentration. A new relationship was proposed to predict the Nusselt number for TiO_2/distilled water nanofluids at turbulent flow regime with considering the microconvection and microdiffusion effects of the dispersed nanoparticles. By using non-linear regression analysis, the constant values of the proposed equation were evaluated. The majority of the computed data falls within 20% and the determination coefficient (R^2) was 1.0. The results also revealed the drag reduction phenomenon in turbulent flow regime in which the friction factors of non-Newtonian nanofluids demonstrated lower trend than those of Newtonian fluid. In addition to the other mechanisms proposed by previous studies, this drag reduction phenomenon might be responsible on the heat transfer enhancement of nanofluids.

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Nomenclature

c_p	Specific heat (J/kg K)
D	Test section inner diameter (m)
f	Friction factor
k	Thermal conductivity (W/m K)
K	Consistency coefficient
L	Test section length (m)
n	Power law index
Pr	Prandtl number
Pe	Peclet number
Re	Reynolds number
Re_g	The generalized Reynolds number
T	Temperature (^oC)
$\bar{u}$	Mean velocity (m/s)

Nu Nusselt number

Greek symbols

ΔP Pressure drop (Pa)
ρ Density (kg/m^3)
μ Dynamic viscosity (Pa s)
τ Shear stress (Pa)
β The shear rate parameter
η Viscosity (mPa s)
ϕ Volume concentration (vol.%)
$\dot{\gamma}$ Shear rate (1/s)

Subscripts

F Fanning
lam Laminar
turb Turbulent
nf Nanofluid
bf Base fluid
np Nanoparticles
a Apparent
w Wall

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