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A COMPARISON ON THE HEAT TRANSFER AND FLOW CHARACTERISTICS OF TiO_2-WATER NANOFLUIDS HAVING TWO DIFFERENT CHEMICAL AGENTS

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ABSTRACT

Heat transfer performance and flow characteristics of aqueous TiO_2 nanofluids with particle volume fraction of 0.2% flowing under turbulent flow regime are investigated. The test section is a 1.5 m long counter-flow double tube heat exchanger. Two different nanofluids are used as working fluids at the same concentration. Firstly, TiO_2 nanoparticles with mean diameters of 21 nm mixed with small amount of CTAB (about 0.01 %) named "SAM 1". Secondly, VP Disp. W740x provided by DEGUSSA AG Company is used and called "SAM 2". The latter mixture is composed of TiO_2 nanoparticle with average diameter of 21 nm dispersed in water. The pH values of nanofluid SAM 1 and SAM 2 are 7.6 and 7.5, respectively. The heat transfer performance and friction characteristics of two samples of nanofluid were presented. In addition, the Nusselt numbers predicted from the published correlation for nanofluids are compared with the present experimental data.

INTRODUCTION

Normally, conventional heat transfer fluids such as oil, water, and ethylene glycol are widely used as the working fluid in many industries applications such as chemical processes, heating and cooling processes, power generation, transportation, electronic cooling, and other micro-sized applications. The heat transfer performance of these fluids depends on their thermophysical properties such as thermal conductivity, heat capacity, viscosity and density. In general, these fluids have inferior thermal properties compared with those of most solids, and this is the primary obstruction for developing the heat transfer equipment. The novel idea to increase of the thermal properties of common fluids by dispersing solid particles in them was first imposed in 1975. Ahuja [1, 2] conducted an experimental study on the heat transfer and flow characteristics of colloidal suspension. A decade later, Liu et al. [3] experimentally investigated the heat transfer and pressure of slurries under turbulent flow regime. Although the suspended particles with millimeter or even micrometer-sized used in their study showed drastically high heat transfer performance, some severe problems such as clogging of flow channels, eroding pipelines, increase in pressure drop and especially poor stability of the suspension were also experienced. About a decade ago, with rapidly development of modern nanotechnology, the particles of the order of nanometer-sized (normally less than 100 nm) were used to replace the particle with micrometer-sized for suspending in the conventional liquids. The common heat transfer fluids with nanoparticles suspension are called nanofluids. This concept was first introduced by Choi [4] in 1995, which has gained popularity later. Compared with millimeter or micrometer sized particle suspensions, a number of researchers reported that the nanofluids have shown number of potential advantages such as better long-term stability, little penalty in pressure drop, and can have significantly larger thermal conductivity. As a result, many researchers have investigated the heat transfer performance and flow characteristics of various nanofluids with different nanoparticles and base fluid materials. The phase change and convective heat transfer behaviors of nanofluids were summarized and shown in our previous papers [5, 6]. Some, Several existing published articles which revealed about the heat transfer performance and flow features were reviewed as follows:

Pak and Cho [7] investigated experimentally the heat transfer performance of γ-Al_2O_3 and TiO_2 nanoparticle dispersed in water flowing in the horizontal circular tube with a constant heat flux under turbulent flow conditions. Li and Xuan [8] and Xuan and Li [9] studied the convective heat transfer and flow features for Cu-water nanofluids flowing through a straight tube under laminar and turbulent flow regimes with a constant heat flux. Tsai et al. [10] studied experimentally gold-DI water nanofluids flowing in a conventional heat pipe with a diameter of 6 mm and a length of 170 mm. Wen and Ding [11] investigated the convective heat transfer coefficient of Al_2O_3-DI water flowing through the copper tube under a constant heat flux under laminar flow regime and emphasized on the entrance region in particular. Yang et al. [12] investigated the convective heat transfer coefficient of graphite nanoparticles (disc-shaped, aspect ratio of about 0.02) in which dispersed in two liquids flowing in a horizontal tube heat exchanger under laminar flow conditions. Ding et al. [13] reported on an experiment in which the local heat transfer coefficient of CNT-distilled water nanofluids flowing through a tube with a 4.5 mm inner diameter under laminar flow regime. Heris et al. [14, 15] studied experimentally the heat transfer performance of Al_2O_3-water and CuO-water nanofluids flowing in an annular concentric tube under constant wall temperature boundary condition for laminar flow regime. He et al. [16] 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 in both the laminar and turbulent flow regime. Nguyen et al. [17] reported on an experiment in which the heat transfer coefficient of Al_2O_3 nanoparticles was dispersed in water flowing through a liquid cooling system of microprocessors or other electronic components under turbulent flow condition. Ko et al. [18] investigated the pressure drop and viscosity of the carbon nanotubes dispersed in distilled water flowing through the horizontal tube and also reported the effect of the CNT concentrations and preparation methods on the viscosity of nanofluids. Chein and Chuang [19] reported the microchannel heat sink (MCHS) performance using CuO-water nanofluids as coolants. Recently, Duangthongsuk and Wongwises [20, 21, and 22] investigated the effect of thermophysical properties models on the prediction of the heat transfer coefficient and also showed the heat transfer performance and friction characteristics of nanofluid, respectively.

All of these articles mentioned above, reported the effect of particle concentrations on the heat transfer performance of nanofluids only. Their results indicated that the heat transfer performance of nanofluids was higher that that of base fluids and the use of nanofluids gave a little penalty in pressure drop. However, Pak and Cho [7] and Duangthongsuk and Wongwises [22] reported that the heat transfer coefficient of the nanofluids were lower than that of pure water. For example, at particle volume fraction of 3 vol.% [7] and 2 vol.% [22], the heat transfer coefficient of nanofluid were about 12% and 14% lower than that of water, respectively. Moreover, focusing on the details of each paper, Yang et al. [12] investigated the effect of the particles sources on the heat transfer characteristics of nanofluids and Ding et al. [13] also reported the effect of pH value on the convective heat transfer of nanofluids. The results of Yang et al. [12] illustrated that one type of nanoparticle gave higher heat transfer coefficient than the other. This difference might be due to particle shape, particle morphology or even solution chemistry. Moreover, the experimental results of Ding et al. [13] showed that the convective heat transfer coefficient at pH=6 was slightly higher than that at pH=10. They also reported that this behavior was unclear if the effect of pH was actually very small under other pH conditions and more experimental work were still needed to confirm this mechanism. In addition, He et al. [16] extensively reported that the effect of pH condition seem to impose little effect on the heat transfer performance of nanofluids under turbulent flow regimes whereas Murshed et al. [23] reported that the pH value of the solutions should be kept low for better heat transfer performance.

As aforementioned, it can be clearly seen that there is no published articles reported about the effect of the chemical agents on the heat transfer and flow characteristics of nanofluids. Therefore, the objective of this paper is to report the effect of the chemical agents on the Nusselt number and flow characteristics of nanofluids.

NOMENCLATURE

Cp	=	specific heat, J/kgK
d	=	particle diameter, m
D	=	tube diameter, m
f	=	friction factor
h	=	heat transfer coefficient, W/m^2K
k	=	thermal conductivity, W/mK
Nu	=	Nusselt number
Pe	=	Peclet number
Pr	=	Prandtl number
q	=	heat flux, W/m^2
Re	=	Reynolds number
T	=	temperature, ^oC

Greek symblos

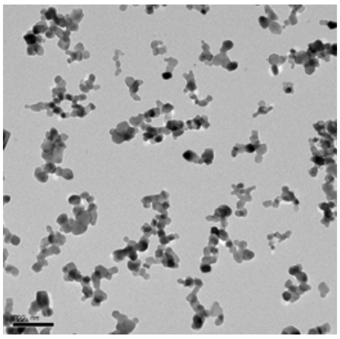
α	=	thermal diffusivity, (m^2/s)
ϕ	=	particle volume fraction
ε	=	tube roughness, (m)
ρ	=	density, kg/m^3
μ	=	viscosity, kg/ms

Subscript

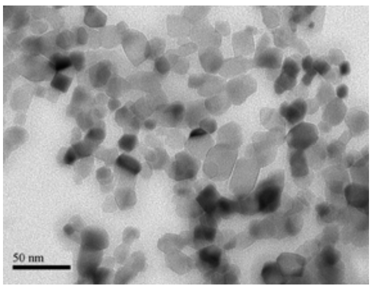
f	=	fluid
p	=	particles
nf	=	nanofluid
w	=	water
wall	=	tube wall

SAMPLE PREPARATION

Preparation of nanofluid is a crucial importance in applying the nanofluid as a working fluid. Normally, there are three effective methods used to attain stability of the suspension as follows: 1) control of the pH value of the suspensions, 2) addition of surface activators or surfactants and 3) use of ultrasonic vibration. The purpose of these techniques is to change the surface properties of the suspended nanoparticles and suppressing the formation of clusters of particles in order to obtain stable suspensions. In this study, two samples of nanofluids were used as testing fluid. The particle concentration of both samples is 0.2 vol.%. For Sample 1 (SAM 1), Degussa P25 TiO_2 nanoparticles with mean diameters of 21 nm were used for dispersing the nanoparticles into the base water. CTAB with very low concentrations (about 0.01%) were used as surfactants and first mixed with water to ensure better stability and proper dispersion of the nanoparticles without affecting the thermo-physical properties of the nanofluid [23]. Following this, the nanofluids were sonicated continuously for two hours using an ultrasonic vibrator in order to ensure complete dispersion. For Sample 2 (SAM 2), nanofluids provided by a commercial source (DEGUSSA, VP Disp. W740x)) were used as working fluid. This mixture was composed of TiO_2 nanoparticles with an average diameter of 21 nm dispersed in water. The original particle concentration was 40 wt%. In order to produce other required particle volume fractions, dilution with water followed by a stirring action was done. Moreover, an ultrasonic vibrator was used to sonicate the solution continuously for about two hours in order to break down agglomeration of the nanoparticles. The pH values of nanofluid SAM 1 and SAM 2 were 7.6 and 7.5, respectively. From the pH values, it could be seen that the solution chemistry of nanofluids was nearly neutral in nature. A transmission electron microscope (TEM) was used to approximate the size of the primary nanoparticles of both samples. As shown in Figs.1a and b**,** it is seen that the primary size of nanoparticles used for both samples are approximately spherical with an average diameter of around 21 nm which is consistent with the identified value from the manufacturer.



a) SAM 1



b) SAM 2

Fig. 1 TEM images of TiO_2 nanoparticles dispersed in water

EXPERIMENTAL APPARATUS AND PROCEDURE

Fig. 2 shows schematic diagram of the experimental system used in the present study. It mainly consists of seven parts as follows: a test section, a magnetic gear pump, two receiver tanks, a cooler tank, a hot water pump, a hot water tank, and a collection tank. The test section was a counter-flow horizontal double tube heat exchanger with 1.5 m length which nanofluid flowing inside the tube while hot water flows in the annular. The outer tube of the test section was made from PVC tubing with 33.9 mm outer diameter and 3 mm thickness while the inner tube was made from copper tubing with a 9.53 mm outer diameter and a 0.7 mm thickness. Plastic tubes were placed at both ends of the test section for minimizing the heat loss along the test section. The pressure drop and the bulk temperature of the nanofluid at inlet and exit of the test section were measured using the differential pressure transmitter and T-type thermocouples, respectively. Similarly, the inner tube wall temperatures along the test tube at different longitudinal positions were measured. In addition, hot water temperatures at inlet and exit of the test section were recorded using T-type thermocouples inserted into the flow directly. The receiver tanks with 60 L capacity were made from stainless steel for receiving the nanofluid and hot water leaving from the test section. The cooler tank with a 4.2 kW cooling capacity and a thermostat was used to control the temperature of nanofluid constant. Similar to the cooler tank, a 3 kW electric heater with a thermostat was installed to keep the temperature of the hot water constant. The speed of the magnetic gear pump was controlled for adjusting the flow rate of nanofluids. A rotameter was used to measure the hot water flow rate while the nanofluid flow rate was evaluated from the time taken for a given volume of nanofluid to be discharged.

In this study, the differential pressure transmitter was calibrated using an air operated dead weight tester. The uncertainty of the pressure measurement is $\pm$ 0.030 kPa. The nanofluid flow rates were determined by electronic balance. The uncertainty of the electronic balance was $\pm$ 0.0006 kg. A portable programmable calibrator was used to calibrate all of the T-type thermocouples with a maximum precision of 0.1 ^{o}C. Therefore, the uncertainties of the measured heat transfer coefficient are around 5%.

During the test, the pressure drop, wall temperatures of the test section, mass flow rates of the hot water and nanofluids, and the inlet and exit temperatures of the hot water and nanofluids were recorded.

DATA REDUCTION

In the present study, both samples of nanofluid with particle volume concentrations of 0.2% were used to determine the effect of chemical agents on the heat transfer performance and flow characteristic of nanofluids. The Nusselt number and friction factor of nanofluids can be computed from the following equation.

$$h_{nf} = \frac{q}{T_{wall} - T_{nf}} \tag{1}$$

$$Nu_{nf} = \frac{h_{nf} D}{k_{nf}} \qquad (2)$$

where h_{nf} is the heat transfer coefficient, q is the heat flux, T_{wall} is the average temperature of the wall, T_{nf} is the bulk temperature of the nanofluid, Nu_{nf} is the Nusselt number, D is the inner diameter of the test tube and k_{nf} is the thermal conductivity of the nanofluid.

Similarly, the friction factor of the nanofluid flowing through the test section is defined as:

$$f_{nf} = \frac{2D\Delta P_{nf}}{L\rho_{nf} u_m^2} \qquad (3)$$

where f_{nf} is the friction factor, ΔP_{nf} is the measured pressure drop, L is the length of the tube, ρ_{nf} is the density of the nanofluid and u_{nf} is the mean velocity of the nanofluid.

The thermophysical properties of nanofluid presented in the above equations are calculated using the following published correlations:

Density and specific heat

The density and specific heat of the nanofluids were calculated from the Pak and Cho [7] correlations,

$$\rho_{nf} = \phi\rho_p + (1-\phi)\rho_w \qquad (4)$$

and

$$Cp_{nf} = \phi Cp_p + (1-\phi)Cp_w \qquad (5)$$

where ϕ is the volume concentration, ρ_w and ρ_p are the densities of the base fluid and the nanoparticles and Cp_w and Cp_p are the specific heat of the base fluid and the nanoparticles, respectively.

Thermal conductivity and Viscosity

The thermal conductivity and viscosity of nanofluids are calculated from Duangthongsuk and Wongwises correlations [24] expressed as:

$$\frac{k_{nf}}{k_w} = a + b\phi \qquad (6)$$

and

$$\frac{\mu_{nf}}{\mu_w} = \left(c + d\phi + e\phi^2\right) \qquad (7)$$

where a, b, c, d and e are constant values as follows:

	For Eq. (6)		For Eq. (7)		
Temp. (°C)	a	b	c	d	e
15	1.0225	0.0272	1.0226	0.0477	-0.0112
25	1.0204	0.0249	1.013	0.092	-0.015
35	1.0139	0.0250	1.018	0.112	-0.0177

The properties of nanofluid shown in the above equation are evaluated from water and nanoparticles at average bulk temperature.

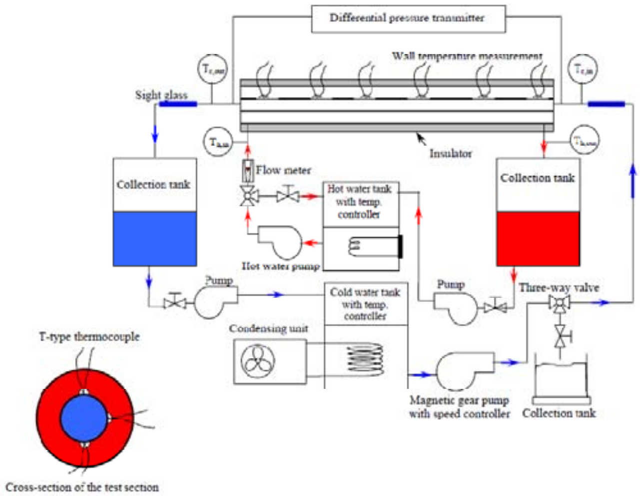


Fig. 2 The experimental apparatus

RESULTS AND DISCUSSION

Before measuring the Nusselt number and friction characteristics of the nanofluid, the reliability and accuracy of the experimental system were estimated by using pure water as the test fluid. The results of the experimental Nusselt number and friction factor were compared with those obtained from the Gnielinski equation [25] and Colebrook's equation [26], respectively. These relations are defined as follows:

The Gnielinski equation is defined as:

$$Nu = \frac{(f/8)(\mathrm{Re}-1000)\,\mathrm{Pr}}{1+12.7(f/8)^{0.5}(\mathrm{Pr}^{2/3}-1)} \qquad (8)$$

where Nu is the Nusselt number, Re is the Reynolds number, Pr is the Prandtl number and f is the friction factor.

Similarly, the Colebrook's equation can be calculated as follows:

$$\frac{1}{\sqrt{f}} = -2.0\log\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{\mathrm{Re}\sqrt{f}}\right) \qquad (9)$$

where ε is the roughness of the test tube.

In addition, the existing correlations for predicting the Nusselt number were used to compare with the experimental results. These correlations are defined as follows:

The Pak and Cho correlation [7] is defined as:

$$Nu_{nf} = 0.021\,\mathrm{Re}_{nf}^{0.8}\,\mathrm{Pr}_{nf}^{0.5} \qquad (10)$$

The Xuan and Li equation [9] is expressed as:

$$Nu_{nf} = 0.0059(1+7.6286\phi^{0.6886}Pe_d^{0.001})\,\mathrm{Re}_{nf}^{0.9238}\,\mathrm{Pr}_{nf}^{0.4} \qquad (11)$$

Finally, Duangthongsuk and Wongwises correlation [22] is defined as

$$Nu_{nf} = 0.074\,\mathrm{Re}_{nf}^{0.707}\,\mathrm{Pr}_{nf}^{0.385}\,\phi^{0.074} \qquad (12)$$

The Reynolds number, Prandtl number, and Peclet number can be calculated from the following equations:

$$\mathrm{Re}_{nf} = \frac{\rho_{nf} u_m D}{\mu_{nf}} \tag{13}$$

$$\mathrm{Pr}_{nf} = \frac{\mu_{nf} Cp_{nf}}{k_{nf}} \tag{14}$$

$$Pe_{nf} = \frac{u_m d_p}{\alpha_{nf}} \tag{15}$$

The thermal diffusivity of the nanofluid is defined as:

$$\alpha_{nf} = \frac{k_{nf}}{\rho_{nf} Cp_{nf}} \tag{16}$$

where d_p is the diameter of the nanoparticles.

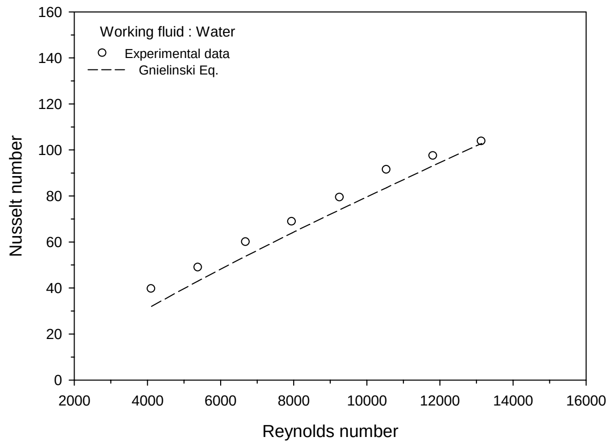


Fig. 3 Comparison between measured heat transfer coefficient and that calculated from Gnielinski eq. [25]

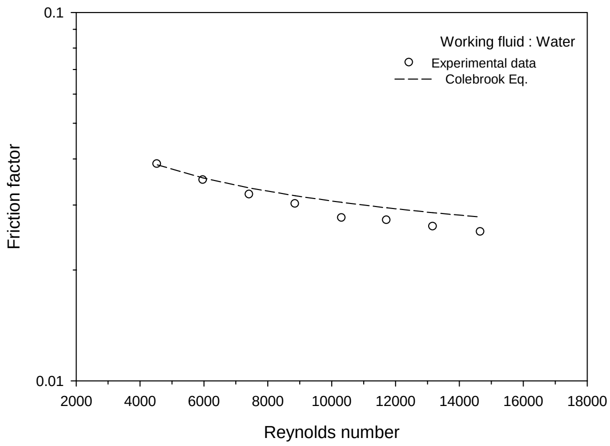


Fig. 4 Comparison between measured friction factor and that calculated from Colebrook eq. [26]

As shown in Figs. 3 and 4, for pure water, the measured Nusselt number and friction factor coincide well with the calculated values.

Fig. 5 shows the comparison of the heat transfer coefficient obtained from water and nanofluids SAM 1 and SAM 2. The results indicate that the heat transfer coefficients of both nanofluids are higher than that of the water at a given Reynolds number. Moreover, the results also show that the heat transfer coefficient of nanofluid SAM 1 is close to the results of nanofluid SAM 2. The authors are quite sure that the surfactant and preparation procedure used for preparing of the nanofluids SAM 1 and SAM 2 are different. Unfortunately, the surfactant and detail of preparation procedure used for Sam 2 are not known. However, the pH values for the both nanofluids are very similar i.e. 7.6 for SAM 1 and 7.5 for SAM 2. In addition, the primary size of nanoparticles used for both nanofluids are about 21 nm. Thus, these are the reason why the heat transfer coefficients of both samples are almost the same.

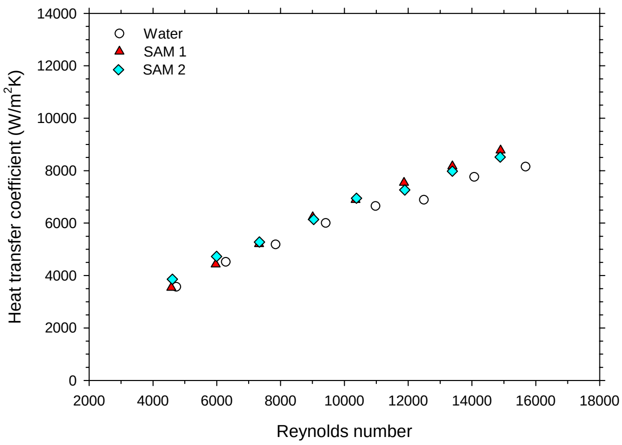


Fig. 5 Experimental heat transfer coefficient for water and nanofluids SAM 1 and SAM 2 versus Reynolds number

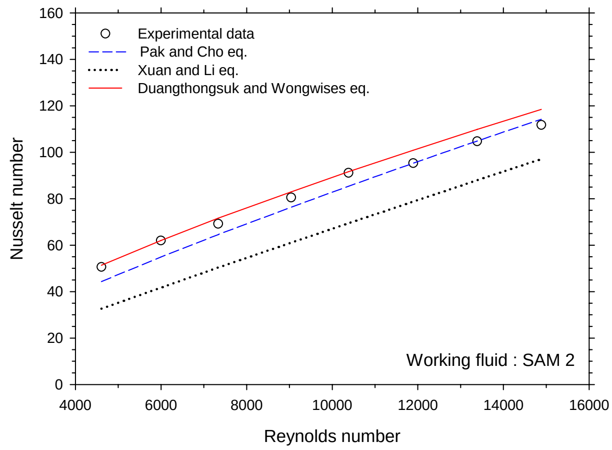


Fig. 6 Comparison of measured Nusselt number and calculated values

As shown in Fig. 6, the calculated Nusselt number from the Pak and Cho [7] and Duangthongsuk and Wongwises [21] correlation are closer to the measured data than the calculated values from Xuan and Li equation [9]. The correlation established by Xuan and Li for turbulent flow of nanofluid gives a lower heat transfer performance than that of the measured data and the preceding equations. This is because the Pak and Cho, and Duangthongsuk and Wongwises correlations were established from the data of TiO_2-water nanofluids whereas the Xuan and Li equation was formed from the data of Cu-water nanofluids.

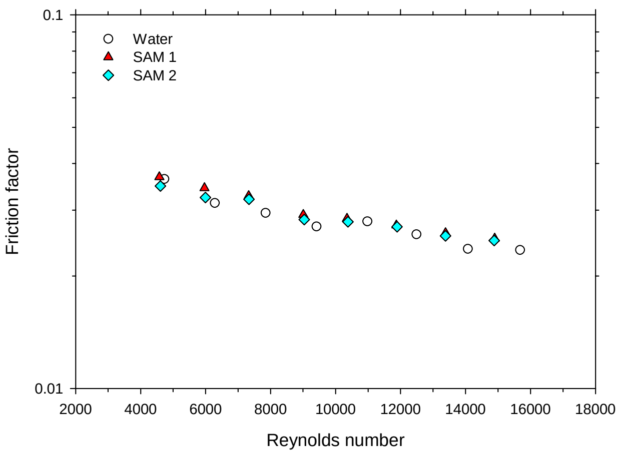


Fig. 7 Comparison of friction factor obtained from water and that from nanofluids SAM 1 and SAM 2

As shown in Fig. 7, the friction factor obtained from the both nanofluids agrees well with those obtained from water data under a given condition. This may be because the small additional nanoparticles in the base liquid do not affect the flow behaviour of the fluid. This means that the nanofluid is not a cause of a penalty drop in pressure. Moreover, comparison between both samples, shows that the friction factor obtained from nanofluid SAM 1 and SAM 2 are almost equal.

CONCLUSION

The effect of two different chemical agents on the convective heat transfer and flow characteristics of nanofluids was experimentally investigated. Nanofluids SAM 1 and SAM 2 with particle concentration of 0.2 vol.% were used as working fluids. The pH values of both samples are 7.6 and 7.5, respectively. The results were compared with the data for pure water. The results illustrate that the heat transfer coefficient of both nanofluids were higher than that of the water. The experimental results also indicate that the heat transfer performance of both solutions is similar in spite of the difference in preparation procedure and chemical agent. Moreover, the results show that the Pak and Cho, and Duangthongsuk and Wongwises correlations for calculating the Nusselt number agree well with the experimental data. In part of flow characteristic, the results show that the pressure drops of the both nanofluids agree well with those of water.

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