Assessment of Aviation Turbine Fuel-TiO_2 Nanofluid for Heat Transfer Augmentation in Rocket Engines

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ABSTRACT
Nanofluids are suspensions of high thermal conductivity nanoparticles in a base fluid, and offer potential to enhance the thermal conductivity and heat transfer performance of the base fluid. The present work measures the thermo-physical properties, heat transfer performance and pressure loss characteristics of Aviation Turbine Fuel (ATF)-titanium oxide (TiO_2) nanofluid. The experimental results show that the enhancement in the thermal conductivity is approximately 15% at a particle volume concentration of 0.3%, whereas the viscosity of the nanofluid increases upto 35% at the same particle volume concentration. Comparing the heat transfer coefficients with those of pure ATF at the same pressure drop, a maximum enhancement of 18% is observed at 0.3% particle volume concentration.

1. INTRODUCTION

Development of energy efficient heat transfer systems is becoming a primary goal of researchers and engineers due to limitation of fossil fuels in the world. In view of this, researchers and engineers have introduced numerous heat transfer augmentation techniques that are both passive and active. Passive techniques use special surface geometries or fluid additives for enhancement. These include extended surfaces, rough surfaces and additives for liquid. Active techniques require external power. Examples of active techniques are surface vibration, fluid vibration and jet impingement. The poor thermal conductivity and heat transfer performance of conventional fluids such as water, ethylene glycol and engine oil in the thermal systems are the main obstacles for their use in recent applications such as microelectronics, transportation, space and HVAC, where space and size of the heat exchanger are the prime objectives of design in addition to efficiency. Recently it has been recognized that the dispersion of nano-sized solid particles in fluids augments the thermal conductivity and heat transfer performance of the conventional fluids. Al_2O_3 and TiO_2 are among the most common nanoparticles used, whereas water and ethylene glycol are the most common base fluids used. We have investigated ATF-Al_2O_3 nanofluids for better heat transfer performance in semi-cryogenic liquid propellant rocket engines [1]. The present work extends the study to ATF-TiO_2 nanofluids for the same application.

Several researchers have studied thermo-physical properties and turbulent heat transfer in water-TiO_2 nanofluids. A brief summary is presented here. Murshed et al. [2] obtained approximately 30% enhancement in the thermal conductivity for water-TiO_2 nanofluid with a particle volume concentration of 5%. Duangthongsuk and Wongwises [3] measured an enhancement of 8% in the thermal conductivity of water-TiO_2 nanofluid at 2% particle volume concentration. Yoo et al. [4] obtained an enhancement of 15% in the thermal conductivity of water-TiO_2 nanofluid at 1% particle volume concentration. He et al. [5] obtained 11.2% enhancement in the thermal conductivity for water-TiO_2

nanofluid with a particle volume concentration of 1.8%. Duangthongsuk and Wongwises [6] have studied heat transfer and fluid flow characteristics of water-TiO_2 nanofluid flowing in a horizontal double tube heat exchanger under turbulent flow conditions. They obtained an enhancement of 26% in the heat transfer coefficient at 1% particle volume concentration. Farajollahi et al. [7] investigated heat transfer characteristics of water-TiO_2 nanofluid flowing in a shell and tube heat exchanger under turbulent flow conditions. Their experimental results showed that the overall heat transfer coefficient of the nanofluid significantly enhances with Peclet number. Heat transfer and pressure loss characteristics of water-TiO_2 nanofluids were studied by Pak and Cho [8]. Their experimental results showed that the Nusselt number of a nanofluid increases with an increase in the Reynolds number as well as with an increase in the particle concentration up to 3%. A heat transfer correlation for the determination of the heat transfer coefficient for the nanofluid was proposed by Pak and Cho based on their experimental results.

The present work reports on the preparation procedure for ATF-TiO_2 nanofluids, a study of their thermo-physical properties (thermal conductivity, specific heat and viscosity), and finally a study of their heat transfer and pressure drop characteristics.

2. PREPARATION OF NANOFLUID

TiO_2 nanoparticles of average particle size 50 nm are purchased from Nanostructured & Amorphous Materials Inc., USA. TiO_2 nanoparticles have excellent chemical and physical stability [2]. Oleic acid, 'Tween' 20 (Polyoxyethylene Sorbitan Monolaurate) and Cetrimide (Tetradecyl Trimethyl Ammonium Bromide) are used as surfactants to prevent the particle agglomeration in the suspension. Numerous trials are carried out to decide the appropriate concentration of surfactants to be used to obtain a stable ATF-TiO_2 nanofluid solution. It is found that the nanofluid with 0.1% volume concentration of TiO_2 particles remains stable for 6 hours after 12 hrs of sonication, if prepared using 1.7 ml each of Oleic acid and 'Tween' 20 and 2 g Cetrimide for 1000 ml ATF.

3. EXPERIMENTAL PROCEDURE

Thermal conductivity of ATF-TiO_2 nanofluid is measured using a transient hot wire apparatus fabricated in the laboratory. Specific heat of ATF-TiO_2 nanofluid is measured using a calorimeter. For measurement of dynamic viscosity of the nanofluid, Micro motion 7829 Visconic Viscometer (Emerson Process Management) is used. The details of the experimental set-ups used for measurement of thermal conductivity, specific heat and viscosity are described in [1]. The procedure and methodology adopted for determination of convective heat transfer performance and pressure drop of ATF-TiO_2 nanofluids are identical to those explained in [1]. An uncertainty analysis [9] of the experimental data is carried out. The maximum uncertainties in mass flow rate, thermal conductivity, viscosity, specific heat, Reynolds number, heat transfer coefficient and Nusselt number are presented in Table 1.

Table 1. Uncertainty analysis results.

Fluid	Maximum uncertainty in % in mass flow rate	Maximum uncertainty in % in thermal conductivity	Maximum uncertainty in % in viscosity	Maximum uncertainty in % in specific heat	Maximum uncertainty in % in Reynolds number	Maximum uncertainty in % in pressure drop	Maximum uncertainty in % in heat transfer coefficient	Maximum uncertainty in % in Nusselt number
ATF	0.9	1.2	4.6	3.7	4.6	1.6	9.9	9.9
ATF+0.1% TiO_2	0.9	1.2	4.0	3.7	4.0	1.6	8.5	8.5
ATF+0.3% TiO_2	0.6	1.2	3.7	3.7	3.7	1.6	8.1	8.1

4. RESULTS AND DISCUSSION

4.1. Thermal conductivity of nanofluid

After validation of the transient hot wire apparatus [1], thermal conductivity of the ATF-TiO_2 nanofluid is measured at particle volume concentrations of 0.1% and 0.3% at three temperatures: 30°C, 40°C and 50°C. These results are presented in Figure 1.

It can be observed from Figure 1 that the enhancement in the thermal conductivity of the nanofluid increases with temperature and particle volume concentration. The results show that the maximum enhancement in the thermal conductivity is approximately 15% obtained at 0.3% particle volume concentration and at 50°C. The enhancement in thermal conductivity may be attributed to the convection caused by the Brownian motion of the nanoparticles in the base fluid [10, 11]. At low temperature (30°C), Brownian motion is less significant resulting in almost identical enhancement in the thermal conductivity at 0.1% and 0.3% particle volume concentration, whereas a difference of approximately 5% is observed in the enhancement in the thermal conductivities at 50°C. A similar trend in the thermal conductivity values is observed by Das et al. in their experiments where they have investigated temperature dependence on water based nanofluids [11]. The comparison between the present experimental results and those predicted from a theoretical model [10] is presented in Figure 2 as a function of temperature.

It can be observed from Figure 2 that the thermal conductivity enhancement values obtained from the theoretical model [10] predict the experimental trend, although the experimental values differ from the predicted ones [10]. The most probable cause for this difference are the assumed values of the parameters that have to be furnished to the model, which may not be appropriate for the present ATF-TiO_2 nanofluids.

4.2. Viscosity of nanofluid

The dynamic viscosity of the ATF-TiO_2 nanofluid is measured at two particle volume concentrations (0.1% and 0.3%) and at three temperatures (30°C, 40°C, 50°C). The percentage increase in the dynamic

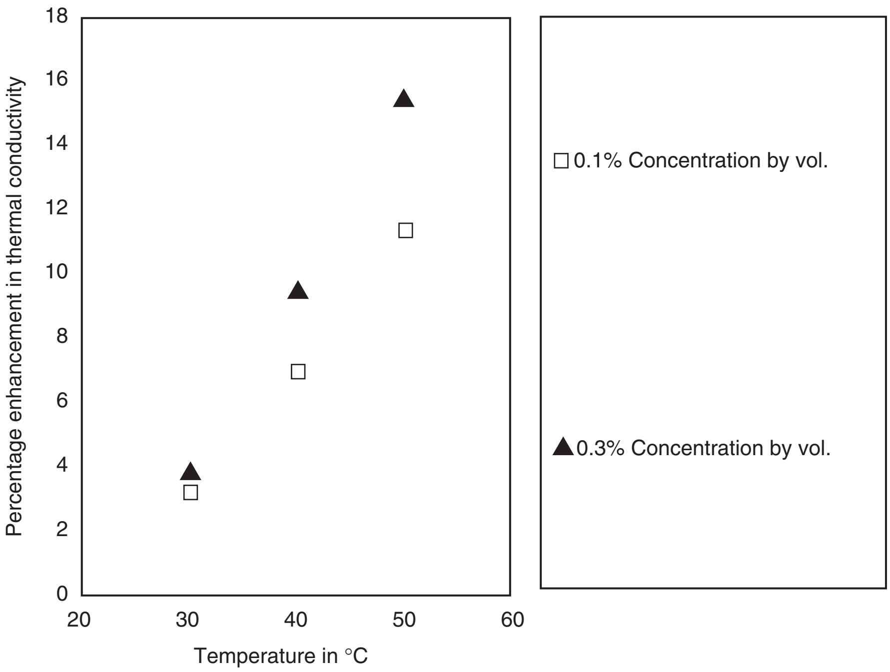

Figure 1. Enhancement in the thermal conductivity of ATF-TiO_2 nanofluid as a function of temperature.

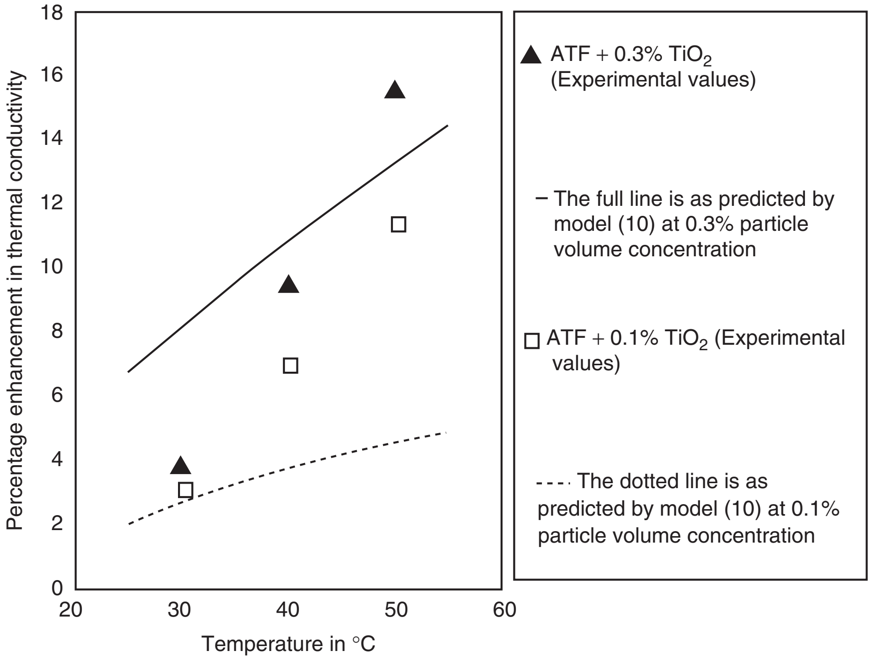

Figure 2. Comparison of measured enhancement in thermal conductivity of nanofluid with that predicted using a model by Prasher et al. [10].

viscosity of the nanofluid as a function of temperature, for different particle volume concentrations is presented in Figure 3.

It can be observed from Figure 3 that the percentage increase in the viscosity increases with an increase in particle volume concentration and temperature, though the dynamic viscosity of the

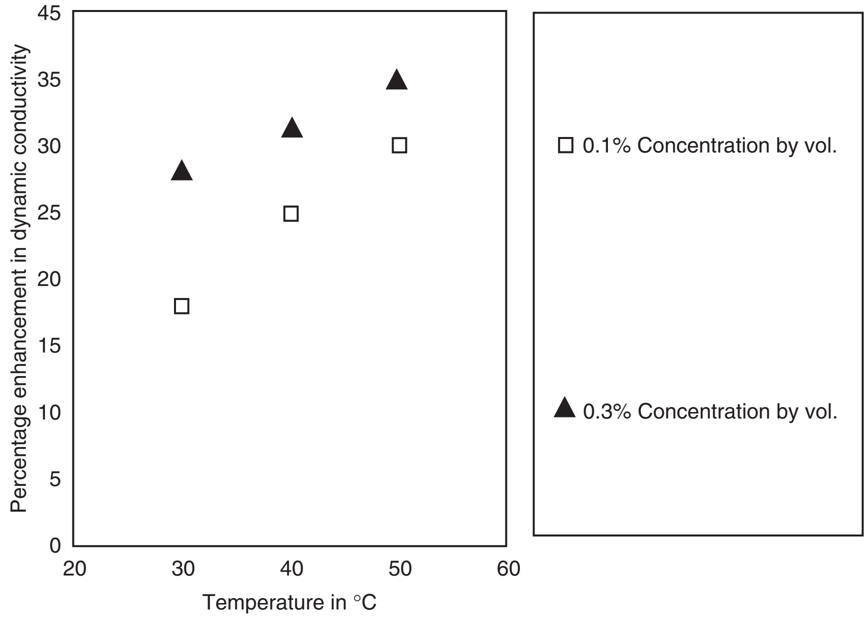

Figure 3. Increase in dynamic viscosity of ATF-TiO_2 nanofluid as a function of temperature.

nanofluid decreases with increase in temperature (this data is not presented here). The effect due to the particle fraction is linked to the fact that increasing concentration would increase the internal viscous shear stresses. As temperature increases, Brownian motion becomes significant which possibly results in increased internal resistance to motion in a nanofluid. A similar effect of increase in dynamic viscosity at higher temperatures can be observed in gases. The experimental results show that a 35% increase in dynamic viscosity is observed at 0.3% particle volume concentration and at 50°C.

4.3. Specific heat of nanofluid

The specific heat of the ATF-TiO_2 nanofluid is measured at particle volume concentrations of 0.1 and 0.3%. The experimental results of measurement of the specific heat of nanofluid are presented in Figure 4 as a function of particle volume concentration. It can be observed from Figure 4 that particle concentration does not show any significant effect on the specific heat of the nanofluid. The measured specific heat of the nanofluid is compared with that obtained from a simple mixing law [12]. Figure 4 shows that the measured values of the specific heat compare well with those obtained from the mixing law.

4.4. Heat transfer performance and pressure drop of nanofluid

After validation of the experimental set-up [1], the convective heat transfer coefficient of the ATF-TiO_2 nanofluid is measured at 0.1% and 0.3% particle volume concentrations. The experiments are performed at a mean temperature of 50°C of the nanofluid, where the "mean" implies the average of the inlet and the outlet bulk-mean temperatures of the nanofluid. The measured values of the convective heat transfer coefficient of the nanofluid as a function of the Reynolds number are presented in Figure 5. It is found that the ATF-TiO_2 nanofluid shows higher values of heat transfer coefficient when compared with ATF at a given Reynolds number. The experimental results show that the maximum enhancement in the heat transfer coefficient is approximately 16% at 0.3% particle volume concentration at the Reynolds number of 13500.

Using the measured values of the convective heat transfer coefficient and thermal conductivity, the Nusselt number of the nanofluid is evaluated at 0.1% and 0.3% particle volume concentrations. Figure 6 presents the Nusselt number of the nanofluid as a function of the Reynolds number for 0.1% and 0.3% particle volume concentrations. The maximum enhancement in the Nusselt number is approximately 5% obtained at 0.3% particle volume concentration. The enhancement in the Nusselt number can be explained using the value of the Prandtl number obtained from the experimental values of dynamic viscosity, specific heat and thermal conductivity. The value of the Prandtl number for pure ATF is 11.3 whereas the

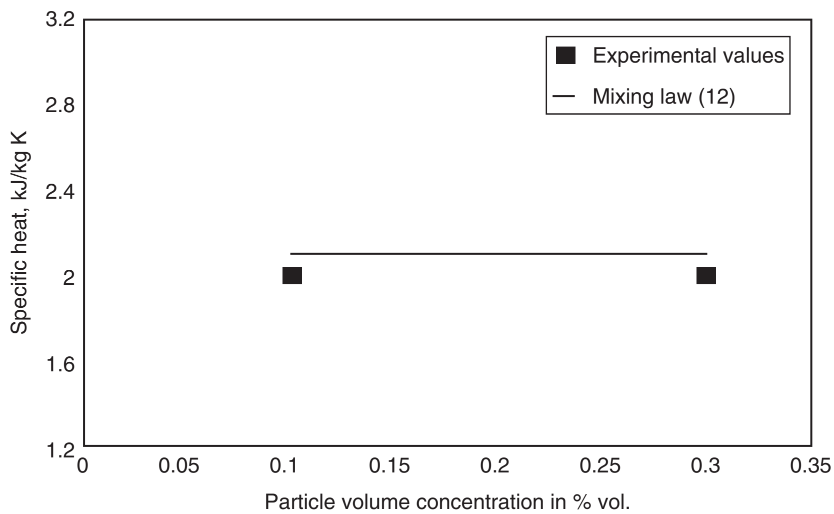

Figure 4. Specific heat of ATF-TiO_2 nanofluid as a function of particle volume concentration.

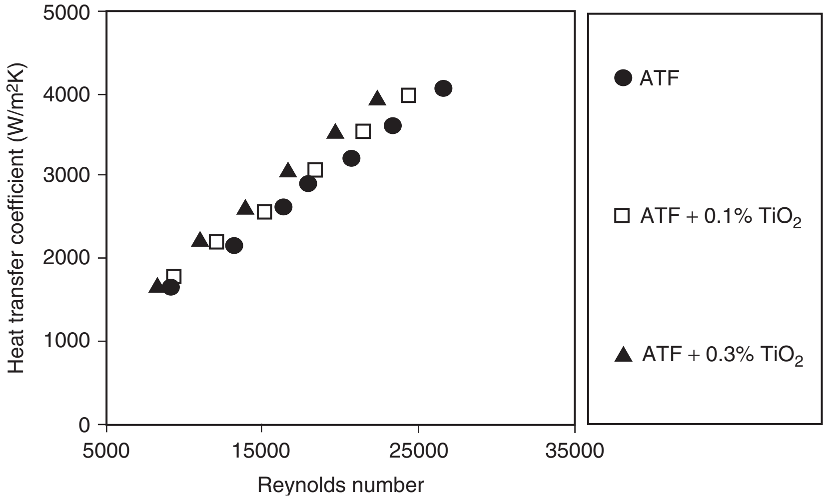

Figure 5. Convective heat transfer coefficient of ATF-TiO_2 nanofluid as a function of Reynolds number.

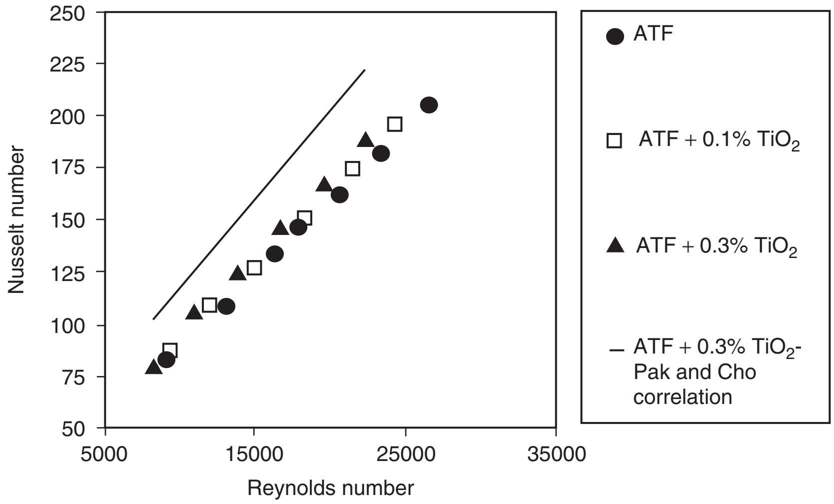

Figure 6. Nusselt number of ATF-TiO_2 nanofluid as a function of Reynolds number.

value of the Prandtl number for the ATF+0.3% TiO_2 nanofluid is 12.1 at 50°C mean fluid temperature. The percentage increase in the Prandtl number is approximately 7% obtained using ATF-TiO_2 nanofluid at 0.3% particle volume concentration. This shows that increase in the Prandtl number leads to an enhancement in the Nusselt number of nanofluid at a given Reynolds number. The measured values of the Nusselt number are compared with those predicted from the Pak and Cho empirical correlation which was obtained using water-TiO_2 and water-Al_2O_3 nanofluids. It can be observed from Figure 6 that the predicted values of the Nusselt number are higher when compared with the measured values at a given Reynolds number. The nanoparticle to base fluid (ATF in the present case as opposed to water in [8]) interaction is possibly the reason for the observed deviation.

The heat transfer performance of the ATF-TiO_2 nanofluid is determined by calculating the ratio of the experimental heat transfer coefficient for the nanofluid to that of the ATF for the same pressure drop. This ratio is denoted as $(h_{nf}/h_{ATF})_{\Delta P}$ and is evaluated for various Reynolds numbers of ATF. The calculated values of $(h_{nf}/h_{ATF})_{\Delta P}$ obtained at 0.1% and 0.3% particle volume concentrations are presented in Figure 7 as a function of the Reynolds number of ATF. It can be observed from Figure 7 that this ratio is higher than 1 for all Re_{ATF} and particle volume concentrations. It is found that the maximum augmentation in the convective heat transfer coefficient is 18% when compared on an equal pressure drop basis. The ratio of Nusselt number of the nanofluid to that of the ATF (Nu_{nf}/Nu_{ATF}) is also determined at the same pressure drop, and is presented in Figure 8 as a function of the Reynolds number of ATF. It can be observed from Figure 8 that this ratio (Nu_{nf}/Nu_{ATF}) is approximately equal to 1. The experimental results reveal that ATF-TiO_2 nanofluid shows better heat transfer performance when compared with pure ATF at the same pressure drop or pumping power, and hence is suitable for heat transfer augmentation applications.

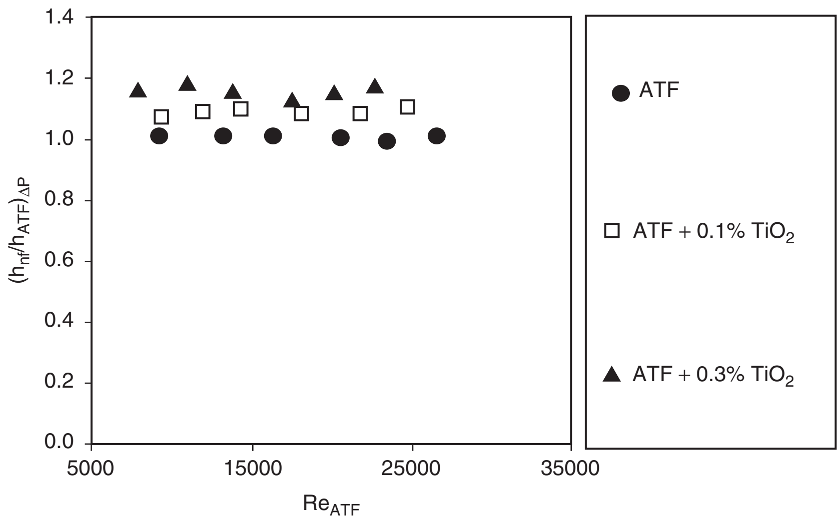

Figure 7. Ratio of heat transfer coefficient of ATF-TiO_2 nanofluid to that of ATF as a function of Reynolds number.

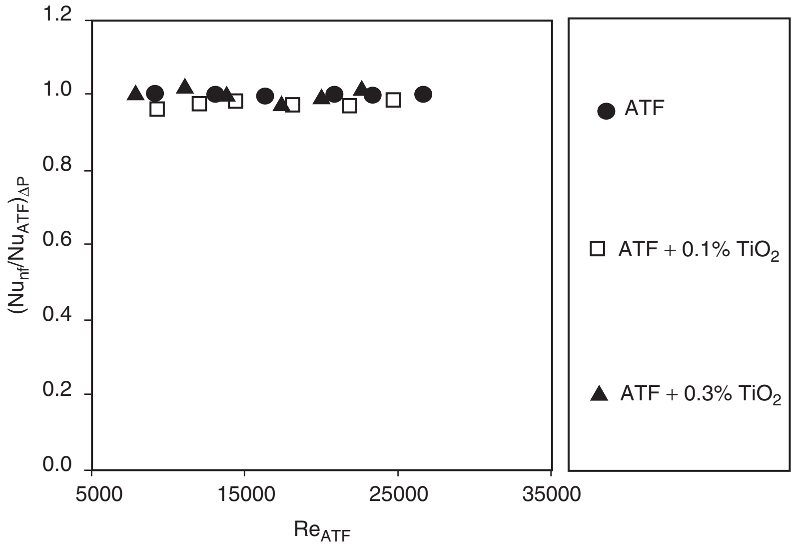

Figure 8. Ratio of Nusselt number of ATF-TiO_2 nanofluid to that of ATF as a function of Reynolds number.

5. CONCLUSION

The thermophysical properties, turbulent heat transfer and pressure drop characteristics of ATF-TiO_2 nanofluid are experimentally investigated for its potential heat transfer augmentation application in semi-cryogenic liquid propellant rocket engines. An enhancement of 15% in thermal conductivity is obtained at 50°C and 0.3% particle volume concentration whereas viscosity of nanofluid increases by 35% at the same conditions. The enhancement in the heat transfer performance is attributed to an enhancement in the value of the Prandtl number due to the addition of nanoparticles. For a given pressure drop, the use of ATF-TiO_2 nanofluid augments heat transfer performance up to 18% whereas Nusselt number is approximately equal to 1 under the same conditions. In conclusion, ATF-TiO_2 nanofluids can be used to obtain better regenerative heat transfer performance in semi-cryogenic rocket engines.

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