

AN EXPERIMENTAL STUDY ON HEAT TRANSFER AND FRICTION FACTOR OF Al_2O_3 NANOFLUID

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ABSTRACT

This paper reports experimental investigations of fully developed laminar convective heat transfer and friction factor characteristics of different volume concentrations of Al_2O_3 nanofluid in a plain tube, fitted with different twist ratios of twisted tape inserts. Experiments are conducted with water and nanofluid in the range of $700 < Re < 2200$, particle volume concentration of $0 < \phi < 0.5\%$, and twisted tape twist ratios of $0 < H/D < 15$. The heat transfer coefficient of the nanofluid is high compared with water, and further enhancement of heat transfer is observed with the twisted tape inserts. Pressure drop is slightly increased with the inserts, but is comparatively negligible. A generalized regression equation is developed based on the experimental data for the estimation of the Nusselt number and friction factor for water and nanofluid in a plain tube with twisted tape inserts.

Keywords: forced convection in a tube, aluminum oxide nanofluid, twisted tape inserts, heat transfer enhancement, nanofluid friction factor.

INTRODUCTION

The low thermal conductivity of conventional heat transfer fluids, such as water, oil, and ethylene glycol, is a serious limitation to the improvement of the performance and compactness of many engineered products, such as heat exchangers. Initial experiments have been performed with small-sized metallic particles, which possess high thermal conductivity, to enhance heat transfer. Early research on the suspension of these micrometer-sized particles identified problems associated with dispersion and flow. To overcome this, nano-sized particles were developed, dispersed in a base liquid, and the thermal conductivity enhancement obtained (Choi, 1995). The thermo-physical properties of different volume concentrations of nanofluid have been explained (Masuda, Ebata, Teramae, & Hishinuma, 1993; Pak & Cho, 1998; Eastman, Choi, Li, Soyez, Thompson, & DiMelfi, 1999; Eastman, Choi, Li, Yu, & Thompson, 2001; Lee, Choi, Li, & Eastman, 1999; Wang, Xu, & Choi, 1999; Das, Putra, Thiesen, & Roetzel, 2003).

The enhancement of thermal conductivity is confirmed by using Al_2O_3 , TiO_2 , and Cu nanoparticles dispersed in water (Pak & Cho, 1998; Xuan & Li, 2003). They also estimated the heat transfer coefficients and pressure drop in tubes, under turbulent flow with nanofluids at different concentrations. The heat transfer coefficients are observed to increase with concentration when compared with base liquid water. The

authors have presented regression equations for the estimation of the Nusselt numbers. Numerical studies have been undertaken (Namburu, Das, Tanguturi, & Vajjha, 2009) with CuO, Al₂O₃, and SiO₂ nanofluids under turbulent flow, which obtained higher heat transfer coefficients compared with water. Experimentally, Wen and Ding (2004) observed that Al₂O₃ nanoparticles, when dispersed in water, show enhancements in the coefficients of laminar convective heat transfer. Experiments conducted by Heris, Esfahany and Etemad (2007) with Al₂O₃/water nanofluid in the laminar flow range of Reynolds number, subject to isothermal wall boundary conditions, predicted higher values of heat transfer. The enhancements were found to increase with Reynolds number as well as with particle concentration. Numerical studies have been undertaken in the laminar range with Al₂O₃/water Al₂O₃/ethylene glycol nanofluids and the heat transfer enhancement obtained.

The numerical analysis of laminar flow heat transfer of Al₂O₃/ethylene glycol and Al₂O₃/water nanofluids in tubes has been reported (Palm, Roy, & Nguyen, 2004; Roy, Nguyen, & Lajoie, 2004) and it was observed that wall shear stress increased with volume concentration and Reynolds number. The enhancement of heat transfer with flow of nanofluids in a tube has been summarized by Wang and Majumdar (2007), and Kakaç and Pramuanjaroenkij (2009). Passive enhancement of heat transfer can also be achieved with the use of twisted tape inserts for flows in a tube or duct. Heat transfer enhancements have been determined through experiment and numerical analysis for the flow of single-phase fluids in a tube, which are valid for a wide range of Reynolds number (Smithberg & Landis, 1964; Lopina & Bergles, 1969; Lecjaks, Machac, & Sir, 1987; Sarma, Subramanyam, Kishore, Dharma Rao, & Kakac, 2003). Experiments have determined the heat transfer using twisted tape inserts in a tube with Al₂O₃ nanofluid at different volume concentrations (Sharma, Sundar, & Sarma, 2009; Sundar & Sharma, 2010). They have presented empirical correlations for the estimation of the Nusselt number and friction factor in the transition and turbulent flow range. The equation proposed by them has the flexibility to estimate the Nusselt number for the flow of water or nanofluid in a plain tube and with twisted tape inserts. Nanofluid heat transfer and pressure drop in the laminar range of Reynolds number with twisted tape inserts has not yet been estimated. The experimental determination of these parameters is undertaken in the present study.

EXPERIMENTAL SETUP AND PROCEDURE

The schematic diagram of the experimental setup is shown in Figure 1a. The fluid flows through a copper tube of 0.012 m diameter to a chiller or collecting tank and a storage tank under the action of a pump. The copper tube is heated uniformly by wrapping it in two 20-gauge nichrome heaters, having a resistance of 53.5 Ω per meter length and 1000 W maximum rating, and subject throughout the entire test section to a constant heat flux boundary condition. The space between the test section and the outer casing is stuffed with rock wool insulation to minimize heat loss to the atmosphere. The 1.5-m length test section is provided with five K-type thermocouples; three brazed to the surface at distances of 0.375, 0.75, and 1.125 m from the entry and two more located to measure the working fluid inlet and outlet temperatures. All these thermocouples have 0.1 $^{\circ}\text{C}$ resolution and they are calibrated before fixing them at the specified locations. The aspect ratio of the test section is sufficiently large for the flow to be hydrodynamically developed. The fluid is forced through the test section under the action of a pump; the suction side is connected to a storage tank. The storage tank is

made of stainless steel with a capacity of 30 liters. The liquid, which is heated in the test section, is allowed to cool by passing it through a chiller. The liquid is then gravity-fed into the storage tank. The provision of the chiller reduces the time required to achieve steady state conditions.

The twisted tapes are made in the laboratory from a 1-mm thick and 0.01-m radius aluminum strip, as shown in Figure 1b. The dimensions of the twisted tape inserts are shown in Table 1. The two ends of a strip were held on a lathe, one at the headstock end and the other at the tailstock end by special devices made in the laboratory. The strip was then subjected to twisting by turning the chuck manually. Four twist ratios of $H/D = 5, 10,$ and 15 were fabricated. Twisted tapes are fitted tightly into the tube and the tape fin effect is neglected.

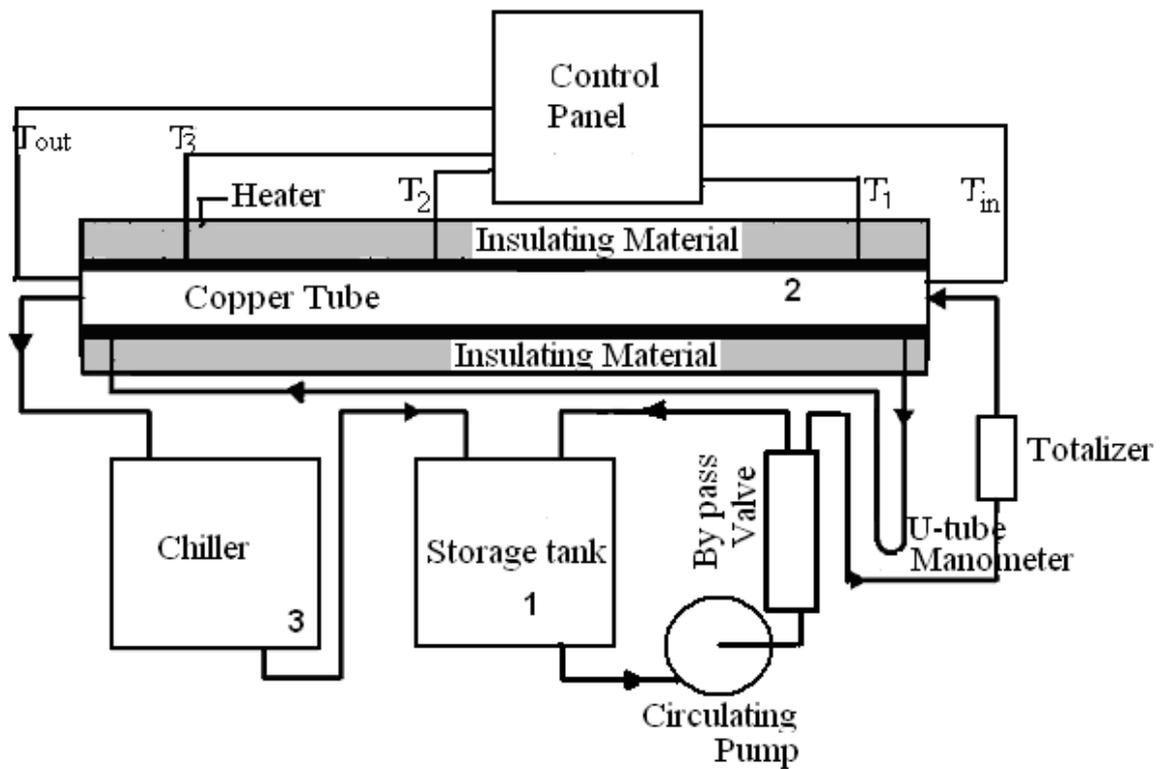


Figure 1a. Schematic diagram of the experimental setup

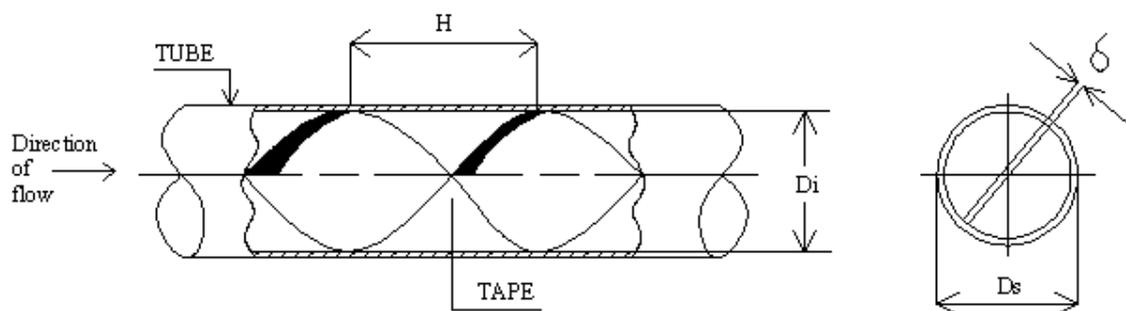


Figure 1b. Full-length twisted tape insert inside a tube

Once the experimental setup is assembled, the storage tank is filled with the working fluid. Experiments are conducted with water and nanofluids to determine the friction factor and heat transfer coefficients for flow in a tube. The procedure for the preparation of nanofluids is followed as described by Sundar, Ramanathan, Sharma and Sekhar Babu (2007). Nanofluids at different volume concentrations of 0.02%, 0.1%, and 0.5% are used in conducting the experiments.

Table 1. Dimensions of twisted tape inserts

S. No.	Parameter	Twist Ratio, H/D, m		
		5	10	15
1	H (Width)	0.05	0.1	0.15
2	D (Diameter)	0.01	0.01	0.01

The working fluid flow rate in the test section is evaluated from the flow meter readings and validated manually. The properties of the fluid are evaluated at the mean temperature, as explained by Sundar and Sharma (2008). The required data for the estimation of the heat transfer coefficients and friction factor are recorded at different flow Reynolds numbers, ranging from 700 to 2200, with flow of water and nanofluid in a tube. A similar procedure is adopted for flow with longitudinal strip inserts and relevant comparisons are made. The heat transfer coefficient is estimated using Newton's law of cooling.

RESULTS AND DISCUSSION

Nusselt number of water and nanofluid in plain tube

The balance between the energy supplied by heating and the energy absorbed by the flowing liquid is established using Eqs. (1) and (2) for each set of data and the experimental heat transfer coefficient estimated using Eq. (3).

$$Q = V \times I \text{ (Energy supplied)} \quad (1)$$

$$Q = m \times C \times (T_0 - T_i) \text{ (Energy absorbed)} \quad (2)$$

$$h_{Exp} = \frac{Q}{A(T_{wall} - T_{mean})}, A = \Pi D_i L, Nu_{Exp} = \frac{h D_i}{k} \quad (3)$$

The deviation between the values obtained with Eqs. (1) and (2) is less than $\pm 2.5\%$ and the heat loss to the atmosphere is neglected. The experimental Nusselt numbers of the fully developed laminar flow with different volume concentrations of nanofluid is shown in Figure 2, together with the data for water. From this figure, it can be observed that the Nusslet number increases with an increase in the volume concentration of nanofluid under the same Reynolds number. The reason for heat transfer enhancement of the nanofluid is due to the effect of thermo-physical properties. Comparatively, the thermo-physical properties are greater for the nanofluid.

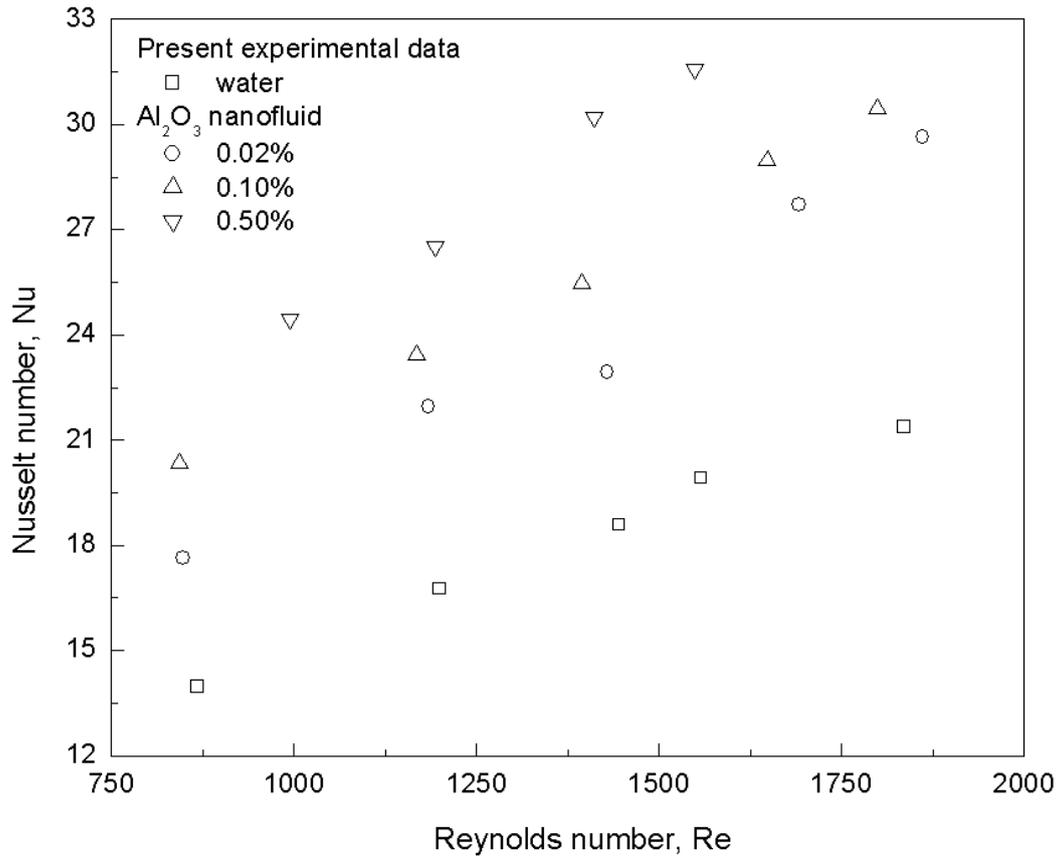


Figure 2. Experimental Nusselt number for water and for different volume concentrations of nanofluid

The equation for the estimation of the Nusselt number for different volume concentrations of Al₂O₃ nanofluid in a plain tube under fully developed laminar flow is obtained with an average deviation (AD) of 2.46% and standard deviation (SD) of 3.23%, given by:

$$Nu_{Re_g} = 0.2624 Re^{0.5860} Pr^{0.3} (0.001 + \phi)^{0.07094} \quad (4)$$

Valid in the range $700 < Re < 2200$, $0 < \phi < 0.5\%$,

The values estimated from Eq. (4) are shown in Figure 3, together with the experimental Nusselt number of water and nanofluid.

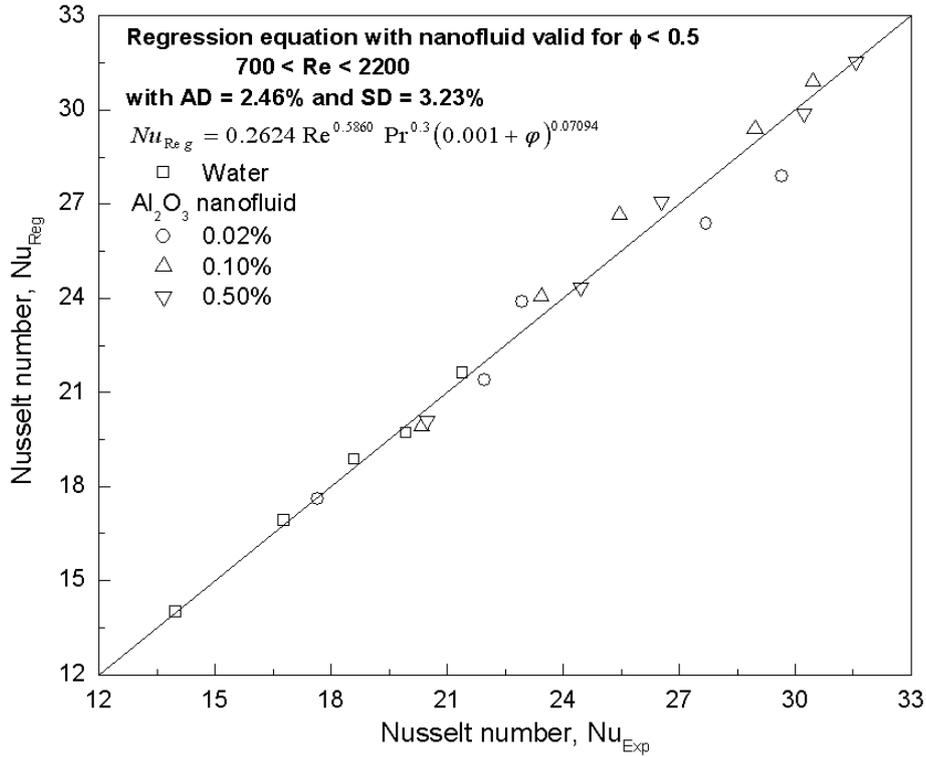


Figure 3. Experimental Nusselt number compared with Eq. (4)

Nusselt number of water and nanofluid in plain tube with twisted tape inserts

Experiments with twisted tape inserts are conducted with water and nanofluid following the procedure explained earlier for flow in a tube. The procedure is repeated with tapes of different twist ratios: 5, 10, and 15. The equation (Sarma et al., 2003) based on theoretical analysis and obtained with a standard deviation of 4% and average deviation of 3% for the estimation of the Nusselt number, is given by:

$$Nu_{Reg} = 0.2036 Re^{0.55} Pr^{0.3} \left(1.0 + \frac{D}{H} \right)^{4.12} \quad (5)$$

This is valid in the range $100 < Re < 3000$, $5 < Pr < 400$, $2.5 < H/D < 10$ for pure liquids.

The experimental Nusselt number of water and nanofluid for flow in a tube with twisted tape inserts is presented in Figure 4; however, no literature is available with which to compare the data. From the figure, it can be observed that higher heat transfer rates are obtained with twisted tape inserts compared with nanofluid flow in a tube. The experimental Nusselt number of water and nanofluid in a plain tube with different twist ratios of twisted tape inserts is shown in Figure 5.

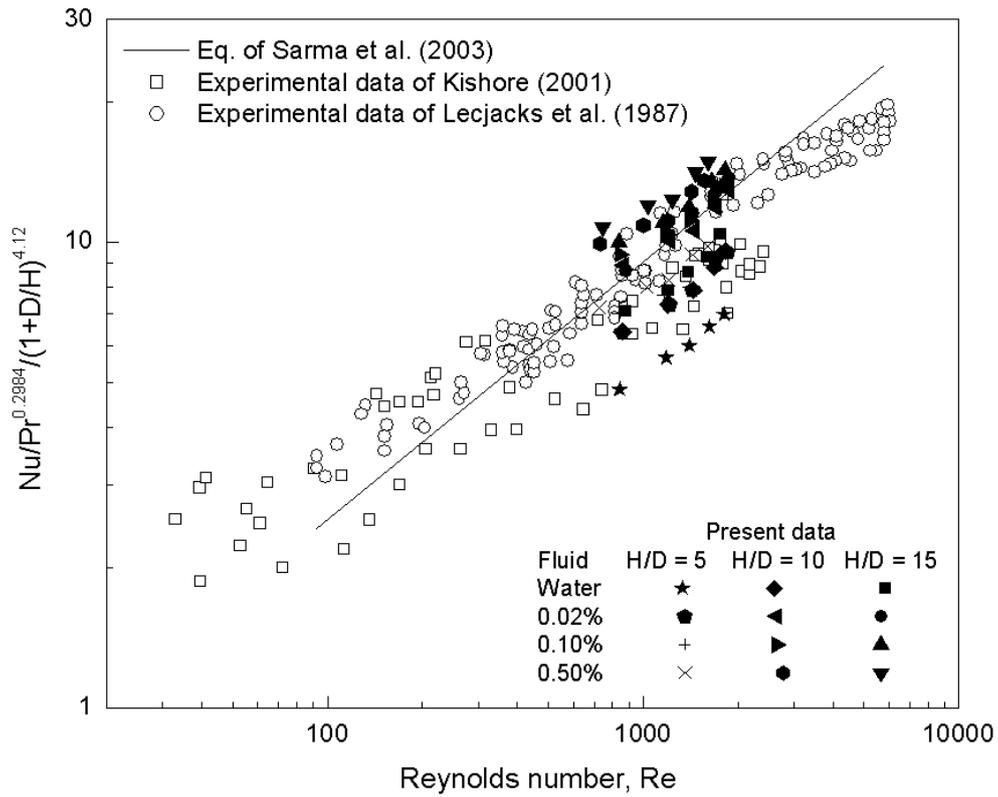


Figure 4. Comparison of present experimental data of water and nanofluid with twisted tape inserts with data available in the literature

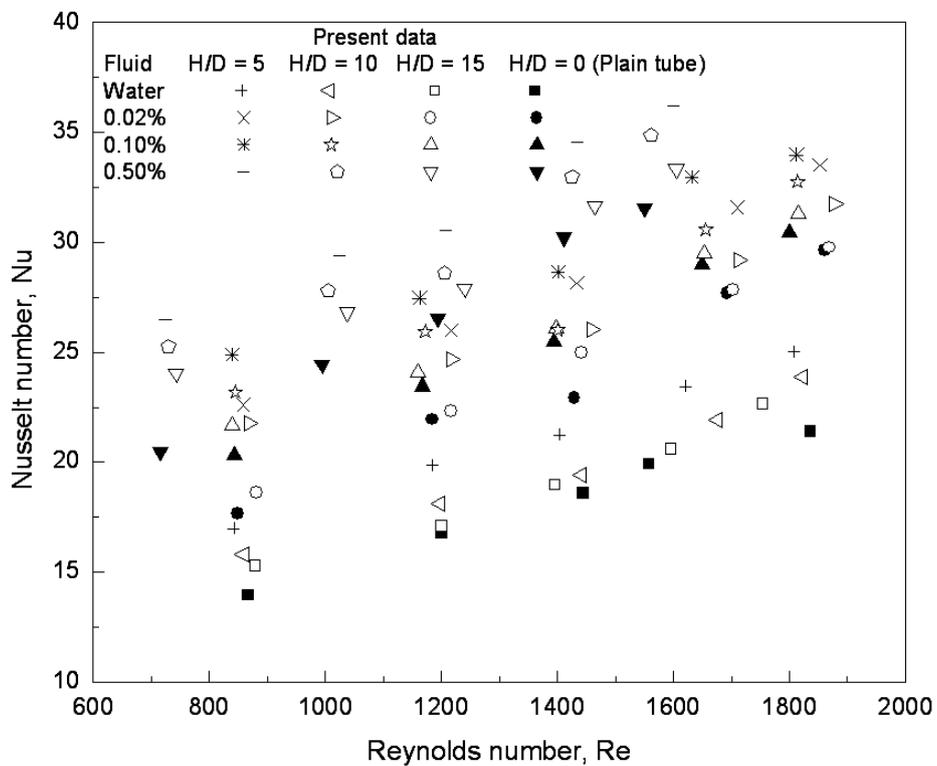


Figure 5. Experimental Nusselt number of water and nanofluid in plain tube with twisted tape inserts

Hence, the present data for the flow of water and Al₂O₃ nanofluid in a tube with twisted tape inserts is subjected to regression and the equation is obtained with an average deviation (AD) of 4.14% and standard deviation (SD) of 5.23%, given by:

$$Nu_{Reg} = 0.5652 Re^{0.5004} Pr^{0.3} (0.001 + \phi)^{0.07060} \left(0.001 + \frac{D}{H} \right)^{0.02395} \quad (6)$$

This is valid in the range $700 < Re < 2200$, $0 < \phi < 0.5\%$, $4.4 < Pr < 6.5$, $0 < H/D < 15$ ($\phi=0$ for water, $H/D=0$ for plain tube). The values of the Nusselt numbers estimated with Eq. (6) are in good agreement with the experimental values shown in Figure 6; thus, validating the developed regression equation.

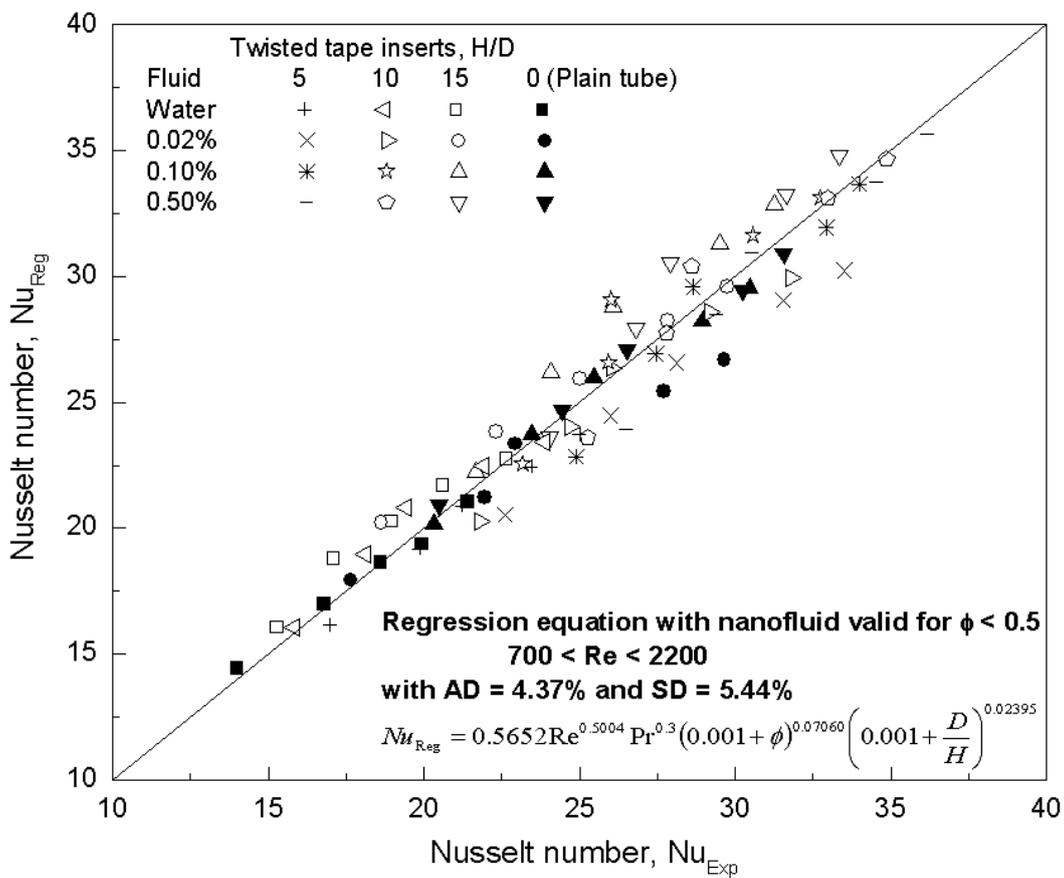


Figure 6. Comparison of experimental Nusselt numbers with Eq. (6)

Friction Factor of Water and Nanofluid in a Plain Tube

The friction factor can be determined from the relation:

$$f = \frac{\Delta P}{\left(\frac{L}{D} \right) \left(\frac{\rho V^2}{2} \right)} \quad (7)$$

where the single-phase fluid friction factor is (Moody, 1944):

$$f = \frac{64}{Re} \tag{8}$$

The experimental friction factor of water and different volume concentrations of nanofluid estimated from Eq. (7) is compared with the values estimated from Eq. (8) and shown in Figure 7. It is evident that the friction factor values for the nanofluid are all the same as the values for water, which means that with the addition of solid particles in the base fluid there is not much enhancement of the friction factor.

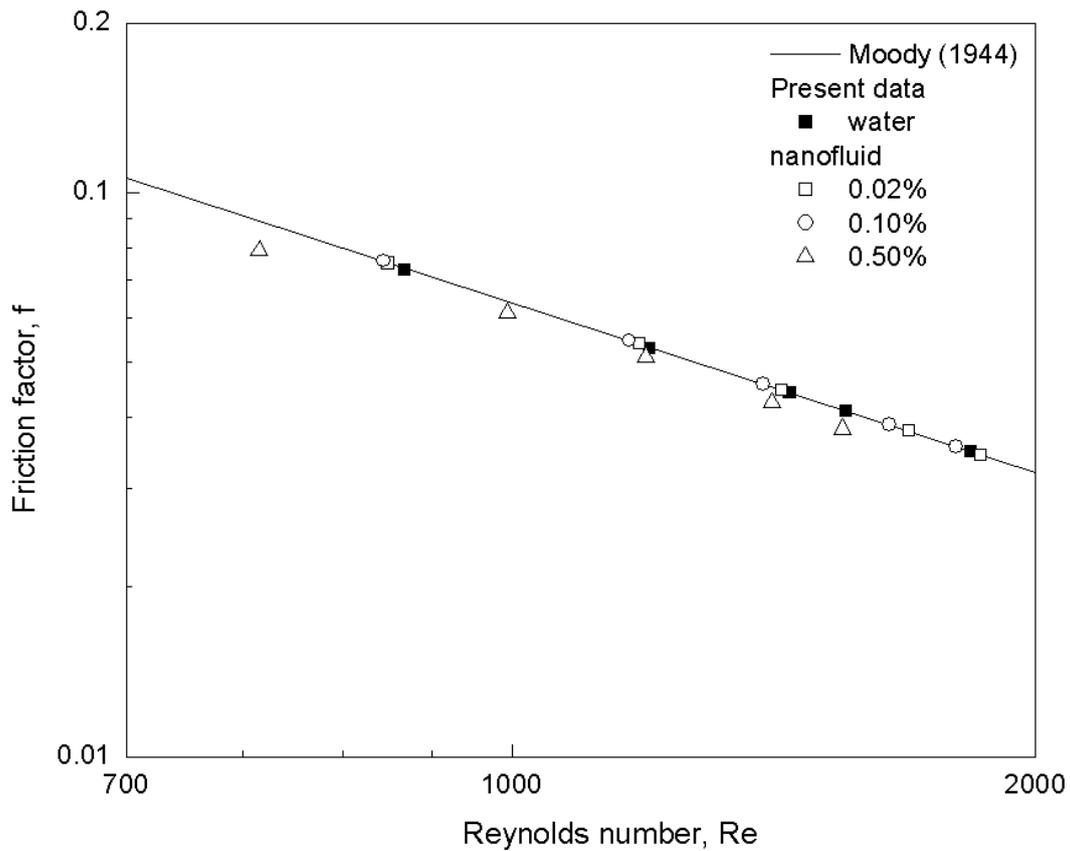


Figure 7. Comparison of experimental friction factor in plain tube with Moody’s (1944) equation

A generalized regression equation is developed for the estimation of the friction factor of water and different volume concentrations of nanofluid in a plain tube under fully developed laminar flow conditions with an average deviation (AD) of 4.552% and standard deviation (SD) of 5.799%, given by:

$$f_{Reg} = 39.54 Re^{-0.9316} (0.001 + \varphi)^{0.01} \tag{9}$$

This is valid for $700 < Re < 2200$, $4.4 < Pr < 6.5$, $0 < \varphi < 0.5$.

The values of the friction factor estimated with Eq. (9) are in good agreement with the experimental values shown in Figure 8; thus, validating the developed equation.

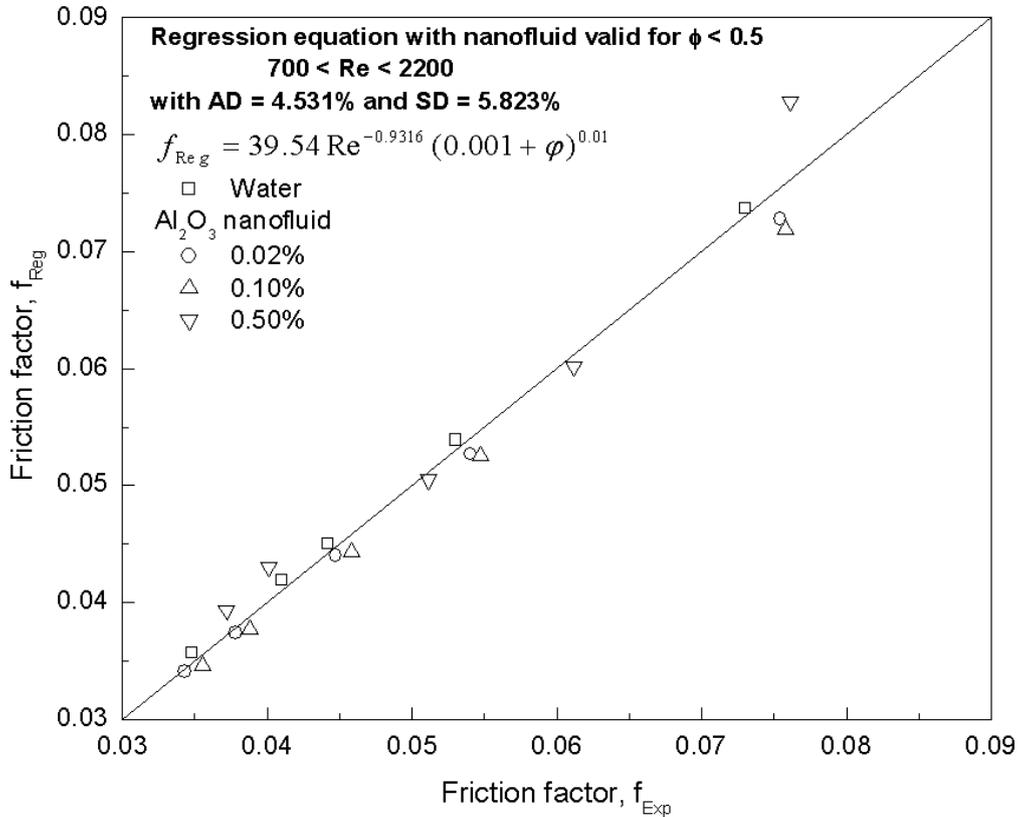


Figure 8. Comparison of experimental friction factor with Eq. (9)

Friction Factor of Water and Nanofluid with and without Twisted Tape Inserts

Equation (7) is used to estimate the experimental friction factor of water and nanofluid in a plain tube with twisted tape inserts, and the data are presented in Figure 9; however, no literature is available with which to compare the data. It is evident that higher friction factors are obtained with twisted tape inserts than with flow in a tube either for water or for nanofluid.

The present data of friction factor are subjected to regression and obtained with an average deviation (AD) of 4.886% and standard deviation (SD) of 6.221%, given by:

$$f_{Reg} = 52.08 Re^{-0.9641} (0.001 + \phi)^{0.01} \left(0.001 + \frac{D}{H} \right)^{0.006120} \quad (10)$$

This is valid for the range $700 \leq Re \leq 2200$, $4.4 \leq Pr \leq 5.5$, $0 \leq \phi \leq 0.5$, $0 \leq (H/D) \leq 15$ ($\phi = 0$ for water, $H/D = 0$ for plain tube). The values of friction factor estimated with Eq. (10) are in good agreement with the experimental values shown in Figure 10; thus, validating the developed equation.

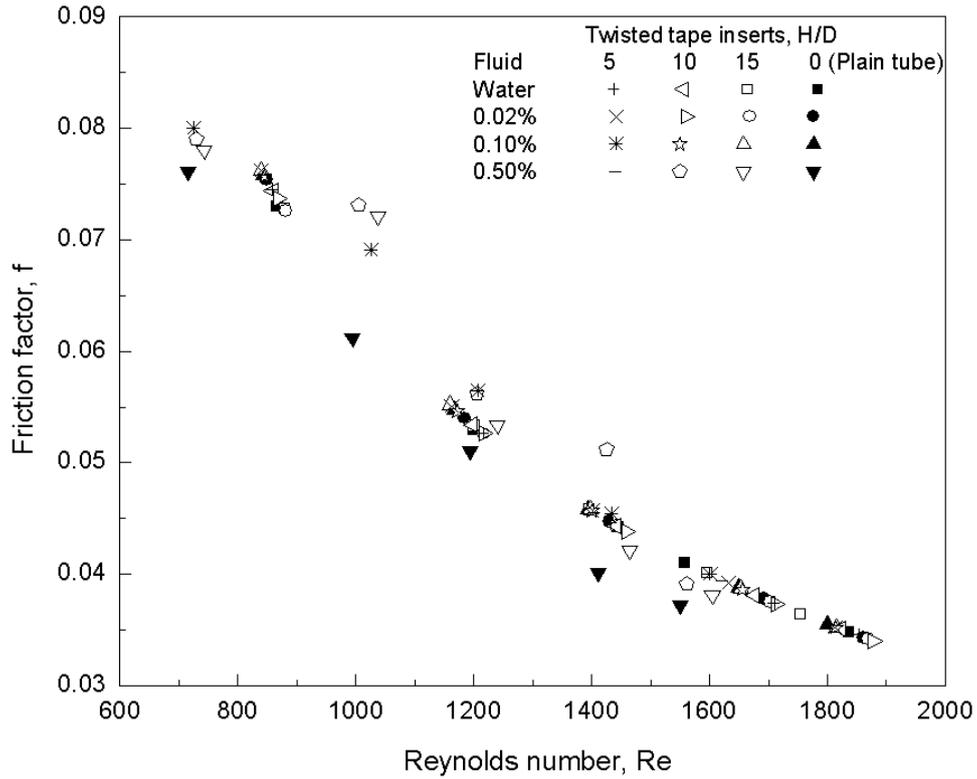


Figure 9. Friction factor of water and nanofluid in plain tube with twisted tape inserts.

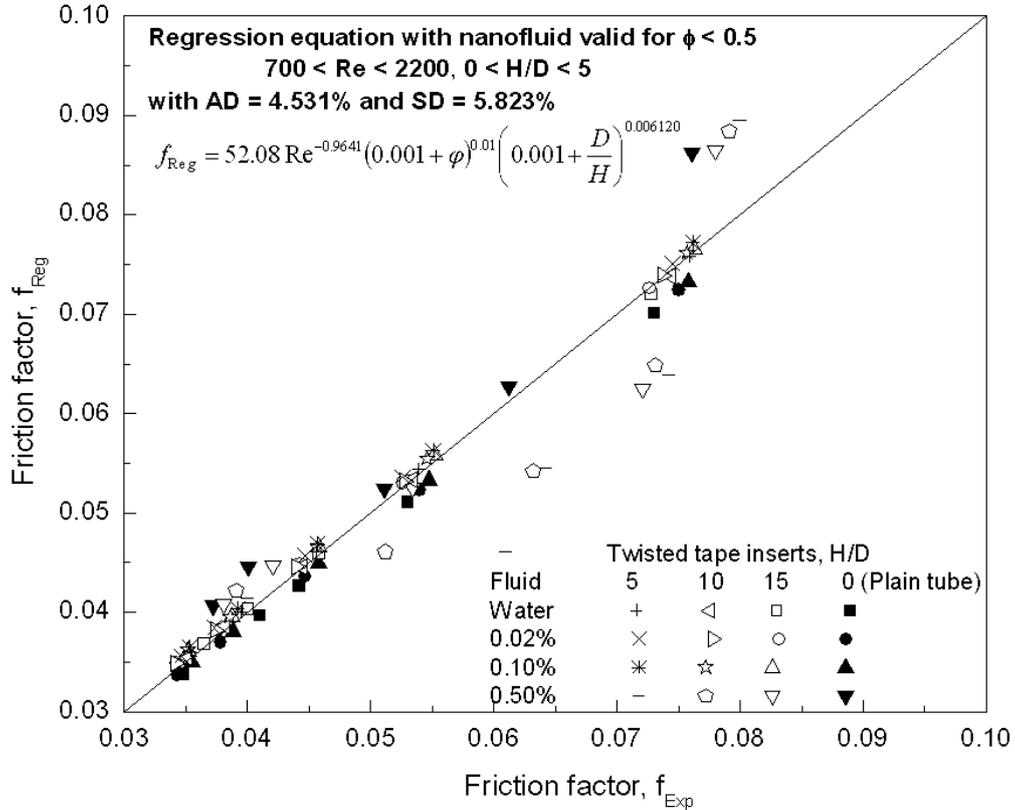


Figure 10. Comparison of experimental friction factor with Eq. (10).

CONCLUSIONS

The enhancement of heat transfer in a plain tube with 0.5% volume concentration of Al_2O_3 nanofluid compared with water for a Reynolds number of 700 and 2200 is 46.52% and 47.59%, respectively. The enhancement of friction factor in a plain tube with 0.5% volume concentration of Al_2O_3 nanofluid when compared with water for a Reynolds number of 700 and 2200 is 1.042 and 1.068 times, respectively. The heat transfer coefficient of 0.5% volume concentration Al_2O_3 nanofluid with twisted tape inserts having $(H/D)=5$ is 14.60% and 29.50% greater for a Reynolds number of 700 and 2200, respectively, compared with the same fluid, and 69.14% and 89.76% greater compared with water flowing in a plain tube. The friction factor of 0.5% volume concentration Al_2O_3 nanofluid with twisted tape inserts having $(H/D)=5$ is 1.0958 times greater for a Reynolds number of 700 and 1.0652 times greater for a Reynolds number of 2200 when compared with water and 1.512 and 1.0412 times greater compared with the same fluid flowing in a tube. The use of twisted tape inserts is advantageous at higher Reynolds numbers based on the values of friction factor and heat transfer compared with flow in a tube either for water or for nanofluid. The use of the nanofluid enhances the heat transfer coefficient with no significant enhancement in pressure drop compared with water in the range tested. The experimental data of friction and Nusselt number of water and Al_2O_3 nanofluid for flow in a plain tube and with longitudinal strip insert can be presented, respectively, as:

$$f_{Reg} = 52.08 Re^{-0.9641} (0.001 + \phi)^{0.01} \left(0.001 + \frac{D}{H} \right)^{0.006120}$$

$$Nu_{Reg} = 0.5652 Re^{0.5004} Pr^{0.3} (0.001 + \phi)^{0.07060} \left(0.001 + \frac{D}{H} \right)^{0.02395}.$$

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Nomenclature

A	area, m ²
C	specific heat, J/kg K
D	inner diameter of the tube, m
f	friction factor
h	convective heat transfer coefficient, W/m ² K
I	current, Amp
k	thermal conductivity, W/m K
L	length of the tube, m
\dot{m}	mass flow rate, kg/s
Nu	Nusselt number, hD/k
Pr	Prandtl Number, $\mu C/k$
Re	Reynolds number, $\frac{4\dot{m}}{\pi D \mu}$
T	temperature, °C
V	voltage, volts
v	velocity, m/sec

Greek symbols

ΔP	pressure drop across the tube
ϕ	volume concentration of nanoparticles, %
μ	dynamic viscosity, kg/m ² s
ρ	density, kg/m ³

Subscripts

Exp	experimental
h	hydraulic diameter
i	inner diameter
m	mean
Reg	regression
W	wall