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Numerical Investigation of the Effect of Twisted Tape in a Tube Using Water-TiO2 Nanofluid on Heat Transfer Enhancement

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Abstract

In this study, effects of inserting twisted tape into a horizontal tube and adding TiO_2 nanoparticle to water on heat transfer enhancement performance and pressure drop penalty are investigated with using CFD program. Analyses are carried out with Reynolds number of in range from 7860 to 15860, and constant heat flux of 50kW/m2K is applied to wall of the tube. To simulate turbulent nanofluid flow k-ω standard turbulent model is applied for all cases. TiO_2 particles with diameter of 10 nm dispersed in water with volume fraction of 0.2% - 2.0% are used as the working fluid. To create swirl flow and enhance heat transfer, the twisted tape (constant twist ratio is y/W=3.0) is used in this study. The results show that adding nanoparticle to water causes to get more convective heat transfer coefficient as from 6% (for 0.2% vol. fract.) to 11% (for 2.0% vol. fract.) in a smooth tube. Furthermore, both adding nanoparticle to water and inserting the twisted tape to the smooth tube causes to 1.44 times greater convective heat transfer coefficient than case of smooth tube and water. In addition to heat transfer performance, pressure drop penalty is investigated in this study. Increasing nanoparticles in the water increase pressure drop penalty slightly, but using twisted tape in the smooth tube increases pressure drop penalty as about 6.5 times more.

Key words

CFD, nanofluid, twisted tape, heat transfer, pressure drop

1. INTRODUCTION

At last decade, energy costs dramatically rise up day by day, since human population increase, and energy sources are consumed. Using the energy efficiently is significantly important for countries that import energy, especially. Heating or cooling systems need so much energy input such as pumping power and electrical resistant for heating, and compressor power for cooling. Within this scope, heat transfer enhanced methods are used and investigated methods. In recent years, nanofluid is used as working fluid for heat transfer devices. Choi [1] is probably the first researcher about the use of particles in nano dimension. Many researchers experimentally studied on this field and reported that nano-particles in the fluids augment heat transfer performance depends on concentration amount, particle size and Reynolds number at last three decades [2-10]. Main reason of using nanofluid is that thermal conductivity property is greater than conventional fluid. Thus, heat transfer performance enhances in comparison with using conventional fluid. The heat transfer enhanced investigations are carried out experimentally and numerically, or both.

Moghadassi et al. [11] investigated numerically the effect of water based Al_2O_3 and Al_2O_3-CuO hybrid nanofluid on forced convective heat transfer. The nanofluid with 0.1 % volume fraction and average particle size of 15nm was considered. Their results showed that higher convective heat transfer coefficient was obtained for Al_2O_3-CuO nanofluid. And they reported that average Nusselt number increase was 4.73% and 13.46% in comparison with Al_2O_3-water and distilled water, respectively. Celen et al. [12] numerically carried out an investigation for TiO_2-water nanofluids in order to observe average temperature, pressure and velocity distribution inside pipe. They used an experimental study data to validate accuracy of numerical methodology. Their results were tolerably as similar as experimental results. Demir et al.[13] searched numerically forced convection flows of nanofluids consisting of water with Al_2O_3 and TiO_2 nanoparticles in a horizontal tube with constant wall temperature used of a single-phase model. Dawood et al.[14] numerically investigated the effect of nanoparticles on heat transfer enhancement in an elliptic annulus, unlike circular pipe. Al_2O_3, CuO, SiO_2 and ZnO were employed as nanoparticles and volume fraction and Reynolds number respectively was ranging from 0.5% to 4% and 4,000 to 10,000. Their numerical results showed that the best heat transfer was obtained for gyliserin-SiO_2 mixture that was volume fraction of 4% and Reynolds number of 10,000.

2. NUMERICAL INVESTIGATION

2.1. Solution Domain

In this study, thermal performance of twisted tape inserted in a horizontal straight tube under constant heat flux is numerically investigated via a CFD program. Working fluid is selected as water and, in addition to twisted tape insert, TiO_2 nanoparticle is added to water. The solution domain 3D geometry is described as in Fig. 1. Smooth tube (ST) and twisted tape inserted tube (TTIT) are illustrated in Fig 2. The twisted tape has y/w ratio of 3.0. y and w represent the pitch length of twisted tape and width of the tape, respectively.

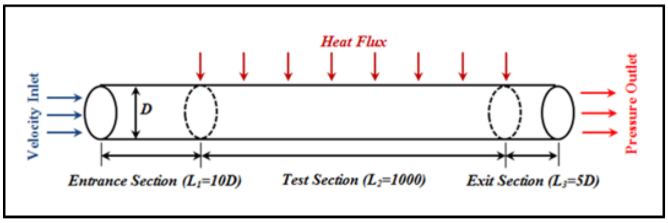

Figure 1. Solution domain and boundary condition types

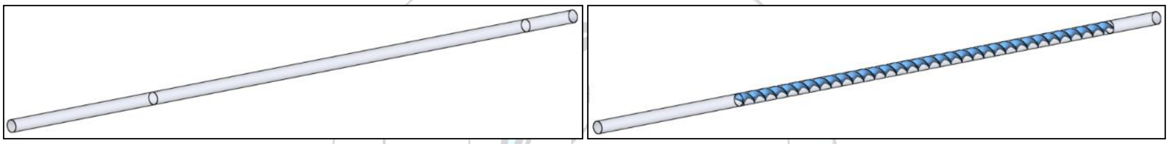

Figure 2. (a) Smooth tube (ST) *(b) twisted tape inserted tube (TTIT)*

The test tube material is aluminum and selected as 19 mm diameter and an entrance section (L_1) is taken as a 10D to supply fully developed flow at the inlet of the test region, test section L_2 is considered as 1m and exit section (L_3) is chosen as 5D to defect the reverse flow. The boundary condition and definition are given in Table 1. Polyhedral mesh structure and boundary layer mesh are created both smooth tube and twisted tape as illustrated in Fig 3.

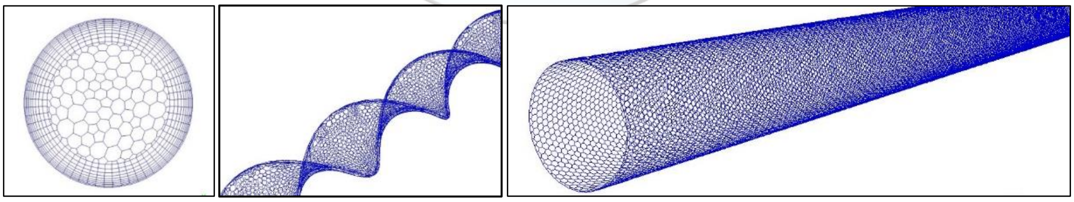

Figure 3. Mesh structure of cross sectional view of (a) the tube at inlet and outlet,(b) outer surface of twisted tape (c) outer surface of tube

Table 1. Boundary condition definitions and values

	Definition	***Value***
D [mm]	Diameter	19
L_1 [mm]	Entrance Section	10D
L_2 [mm]	Test Section	1000
L_3 [mm]	Exit Section	5D
q'' [kW/m^2K]	Constant Heat Flux	50
Inlet Velocity magnitude [m/s]	Velocity Inlet	Calculated depends on Re
Gauge Pressure [Pa]	Pressure Outlet	0

2.2. Data Reduction and Thermo-Physical Properties of Nanofluid

The CFD program uses differential equation to simulate and calculate flow characteristic and thermal occurrences. Used conversation equations in CFD program are as follows:

Conservation of mass equation [15]:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = 0 \tag{1}$$

Conservation of momentum equation [15]:

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla(\rho \vec{v}\vec{v}) = -\nabla P + \nabla(\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F} \tag{2}$$

Energy equation [15]:

$$\frac{\partial}{\partial t}(\rho E) + \nabla\big(\vec{v}(\rho E + p)\big) = \nabla\big(k_{eff}\nabla T - \textstyle\sum_j h_j \vec{J}_i + (\bar{\bar{\tau}}_{eff}.\vec{v})\big) + S_h \tag{3}$$

The results were compared with S. Eimsa-ard [16] et al. and commonly used equations that are Gnielinski Eq. (6) and Blasius Eq. (7) in terms of Nusselt number (4) and friction factor (5), respectively.

$$Nu = \frac{hD}{k} \tag{4}$$

$$f = \frac{\Delta P}{\frac{1}{2}\rho V^2 \frac{L}{D}} \tag{5}$$

Gnielinski Equation [17]:

$$Nu = \frac{\left(\frac{f}{8}\right)(Re-1000)Pr}{1+\left[12.7\left(\frac{f}{8}\right)^{0.5}(Pr^{2/3}-1)\right]} \tag{6}$$

Blaisus Eq. [18]:

$$f = 0.316Re^{-0.25} \tag{7}$$

2.3. Validation of the numerical methodology

To ensure validation of the numerical methodology, especially including fluid mechanics problems turbulence model should be determined, and experimental results or empirical correlations can be used for comparing numerical results. In this context, different turbulence models are tested, and k-w standard model is most matching model with reference results. Validation of the numerical study for smooth tube and water is given in Fig 4 and 5 in terms of Nusselt number and friction factor, respectively. As can be seen in these figures, a good agreement is ensured for proving accuracy of numerical methodology.

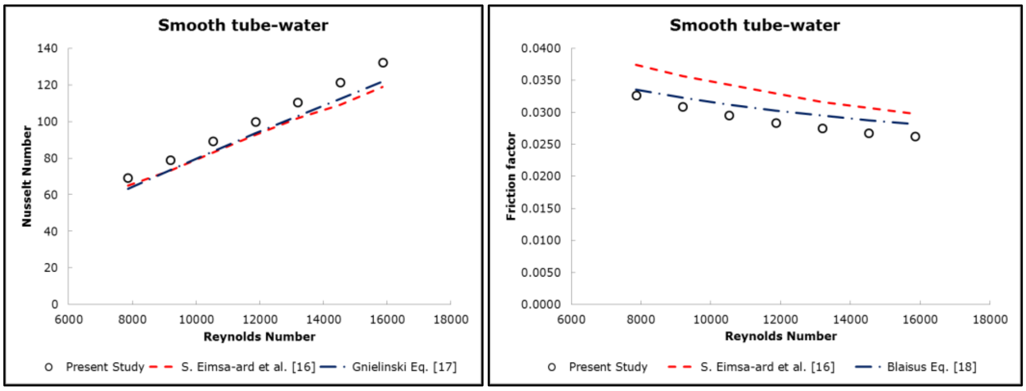

Figure 4. Numerical results for smooth tube and water in terms of (a) Nusselt number (b) friction factor

Mixture approach is employed to model nanofluids, and properties of fluid are applied as independent in temperature. Validation of nanofluid with different fraction (φ=0.002, 0.006, 0.01 and 0.02) and different nanoparticles is illustrated in Fig. 5. Good agreement is observed between the result of present study and the other studies. Thermo-physical properties of nanofluid is calculated with following equations:

Density of nanofluid:

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi\rho_{np} \tag{8}$$

Specific heat of nanofluid:

$$Cp_{nf} = \frac{(1-\varphi)(\rho_{bf})(Cp_{bf})+(\varphi\rho_{np})(Cp_{np})}{\rho_{nf}} \tag{9}$$

Thermal conductivity:

$$k_{nf} = k_{bf}\frac{[k_{np}+(n-1)k_{bf}-(n-1)\varphi(k_{bf}-k_{np})]}{[k_{np}+(n-1)k_{bf}+\varphi(k_{bf}-k_{np})]} \tag{10}$$

$$n = 3/\psi \tag{11}$$

where n is the empirical shape factor and ψ is the sphericity, defined as the ratio of the surface area of a sphere to the surface area of the particle (Eq. 11), as stated by Duangthongsuk and Wongwises [19]. The sphericity value assumed as 1. Expressions of knf, knp and kbf are the thermal conductivity of nanofluid, nanoparticle and base fluid, respectively. Dynamic viscosity of hybrid nanofluid does not need to calculate again due not to including expect of volume fraction (φ) in the formula.

Dynamic viscosity:

$$\mu_{nf} = \mu_{bf}(123\varphi^2 + 7.3\varphi + 1) \tag{12}$$

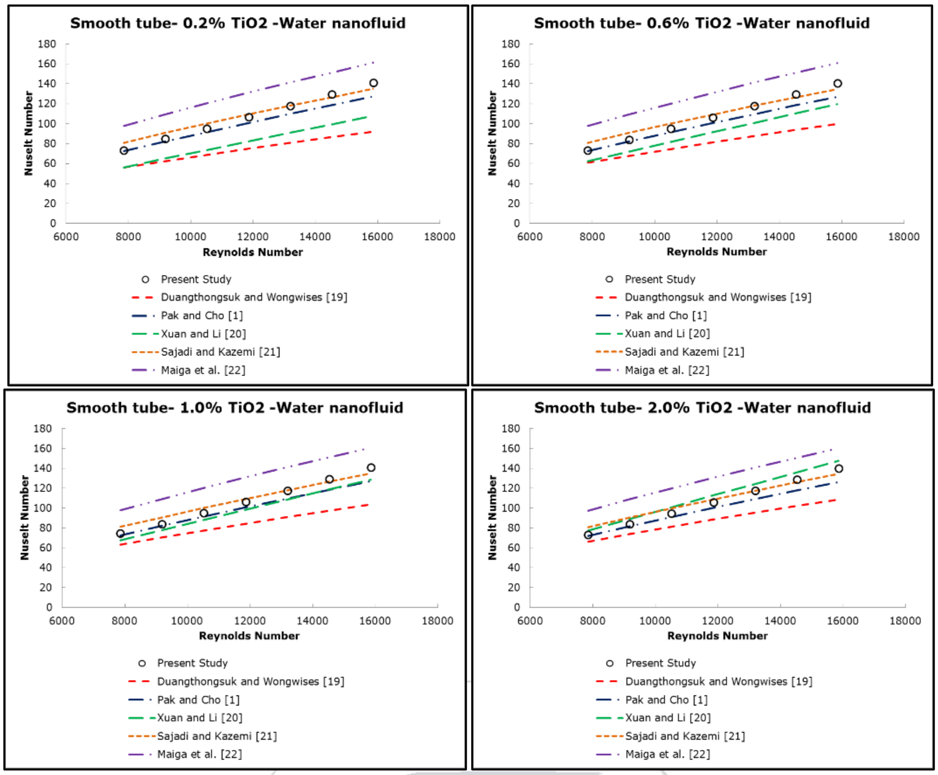

Figure 5. Validation of numerical results for smooth tube and TiO_2-water nanofluid in terms of Nusselt number versus Reynolds Number

In addition to nanofluid investigation, twisted tape effect is investigated in this study. Twisted tape inserted tube through water flow validation is ensured with Manglik and Bergles Eqs. [23] in terms of Nusselt number (13) and friction factor (14), as illustrated in Figure 6.

$$Nu = \left(1 + \frac{0.769}{\frac{y}{w}}\right)\left[0.023Re^{0.8}Pr^{0.4}\left(\frac{\pi}{\pi-4\delta/D}\right)^{0.8}\left(\frac{\pi+2-2\delta/D}{\pi-4\delta/D}\right)^{0.2}\right] \tag{13}$$

$$f = \left(1 + 2.06\left(1 + \left(\frac{2(y/w)}{\mu}\right)^{2}\right)^{-0.75}\right)\left[0.079Re^{-0.25}\left(\frac{\pi}{\pi-4\delta/D}\right)^{1.75}\left(\frac{\pi+2-2\delta/D}{\pi-4\delta/D}\right)^{01.25}\right] \tag{14}$$

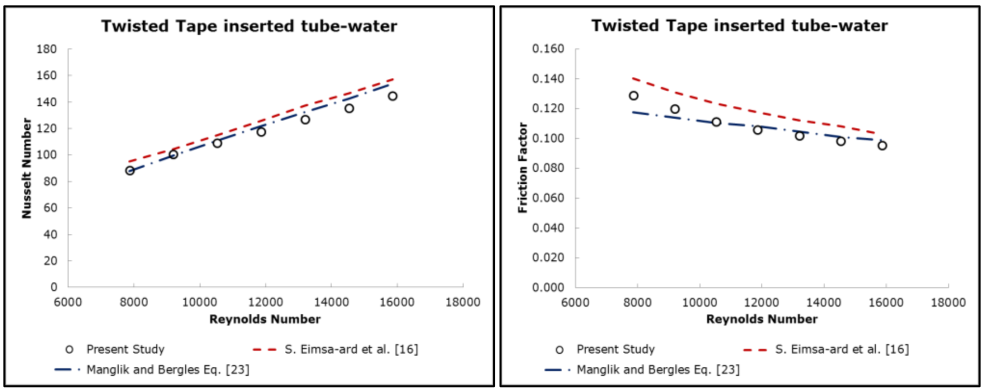

Figure 6. (a) Nusselt number results for TTIT *(b) Friction factor results for TTIT*

3. RESULTS AND DISCUSSIONS

In this study, numerical investigation of effects of both TiO_2-water nanofluid and twisted tape on thermal and hydraulic performance is carried out by using a CFD program. The nanofluid volume fraction is considered in range from 0.002 to 0.02. With developing nano technology, nanofluids have been used in heat transfer mechanisms. Because thermal conductivity of working fluid increases, heat transfer enhances for these systems. Numerical results of TiO_2-water nanofluid through the smooth tube are given in terms of heat transfer coefficient and pressure drop in Fig 7 and 8, respectively. With increment of nanoparticle into water, heat transfer coefficient increases for increment of Reynolds number. Pressure drop increases with increment of nanoparticle into water, due to viscosity and density of the fluid increase.

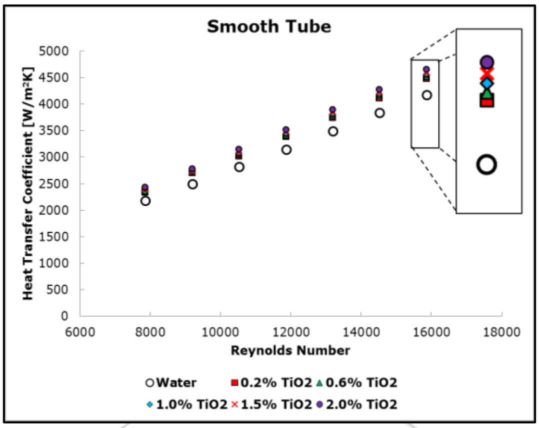

Figure 7. Results of TiO_2-water nanofluid through the smooth tube in terms of heat transfer coefficient versus Reynolds number

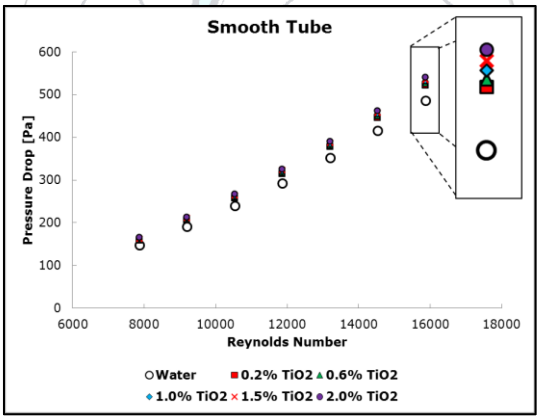

Figure 8. Results of TiO_2-water nanofluid through the smooth tube in terms of pressure drop versus Reynolds number

In order to enhance heat transfer performance, turbulators like twisted tape insert are widely used. The twisted tape physically enhanced heat transfer by destructing thermal and hydraulic boundary layer near the inner surface of the tube. The effect of twisted tape in terms of heat transfer coefficient and pressure drop is given in Fig 9 and 10. The twisted tape inserts in tube create swirl flow, and because of that secondary flow occurs. With occurrence of the secondary flow, the fluid more contacts with heated wall and spends more time until leave the tube. The swirl flow and secondary flow is depicted in Figure 11 and 12, respectively. In other hand, inserting twisted tape cause to increase pressure drop penalty. It is expected result, because the flow counters with an obstacle surface in the flow direction.

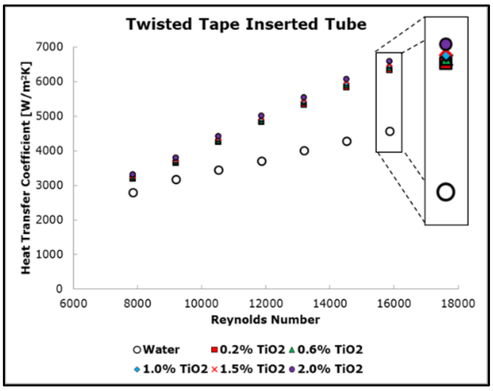

Figure 9. Results of TiO_2-water nanofluid through the twisted tape inserted tube in terms of heat transfer coefficient versus Reynolds number

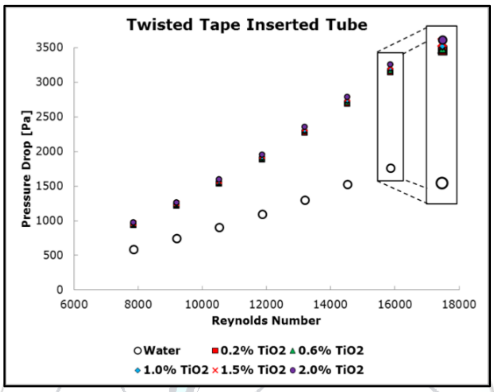

Figure 10. Results of TiO_2-water nanofluid through the twisted tape inserted tube in terms of pressure drop versus Reynolds number

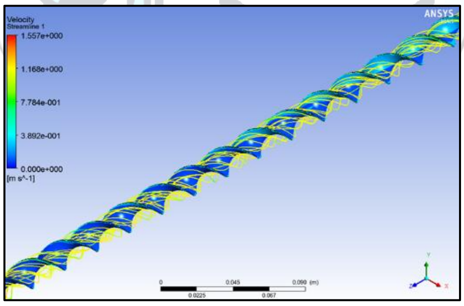

Figure 11. Swirl flow due to twisted tape through the tube

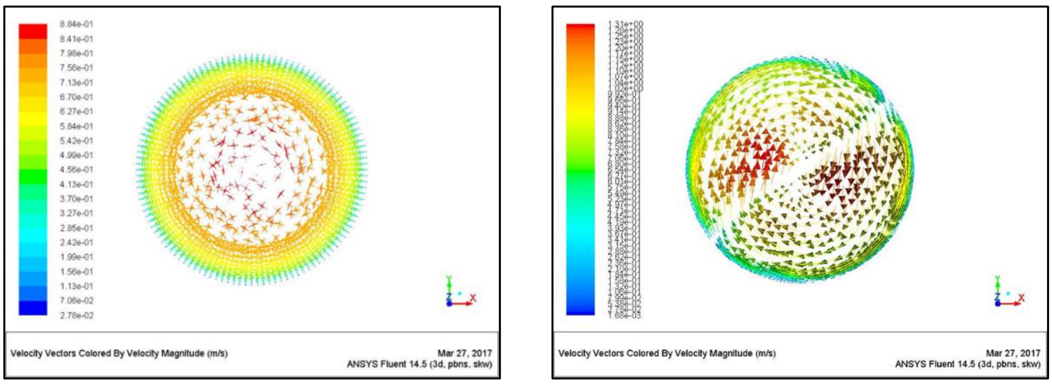

Figure 12. (a) Velocity vector contour of the smooth tube; (b) Velocity vector contour twisted tape inserted tube

4. CONCLUSION

In this study, effect of TiO_2-water nanofluid and twisted tape insert on heat transfer and pressure drop is numerically investigated by using mixture phase model. Results showed that convective heat transfer enhances for all considered volume fraction of TiO_2 nanofluid with increasing Reynolds number. Major reason of the heat transfer enhancement is that thermal conductivity of the nanofluid is so greater than distilled water. Furthermore, with inserting twisted tape into smooth tube, it is purposed generating secondary flow. Maximum heat transfer coefficient is obtained as 6593 W/m^{2}K for the case of twisted tape inserted tube volume fraction 2.0, Reynolds number of 15,860. This value is 1.44 times greater than smooth tube for same Reynolds number.

The main findings can be summarized as physical (inserting twisted tape) and chemical (adding nanoparticle) reasons at below:

- ✓ Inserting a twisted tape in a tube increases heat transfer and pressure drop.
- ✓ The main reason of increasing heat transfer is destructing the boundary layer and occurring secondary flow.
- ✓ Maximum heat transfer coefficient is obtained as 6593 W/m^{2}K for Reynolds number of 15860. This value is 1.44 times greater than smooth tube for same Reynolds number.
- ✓ The main reason of increasing pressure drop is that flow encounter with an obstacle surface, and increasing static pressure through the tube.

In terms of chemical reasons

- ✓ Adding nanoparticle up to volume fraction of 2.0% into water, increases the heat transfer, as well. The main reason of this result is that thermal conductivity of the nanofluid increases, and because of that, heat transfer occurs more effectively between the molecules.
- ✓ Adding nanoparticle into water slightly increase the pressure drop in comparison with heat transfer. The reason of increasing pressure drop is related with increasing viscosity and density of the nanofluid.

NOMENCLATURE

Abbreviation	*definition*	*unit*
Cp	specific heat,	[J/kg K]
D	tube diameter,	[m]
f	friction factor	[-]
h	heat transfer coefficient,	[W/m^{2}K]
k	thermal conductivity,	[W/mK]
L	length of the test tube,	[m]
N	empirical shape factor	[-]
Nu	Nusselt number	[-]
ΔP	Pressure drop,	[Pa]
Pr	Prandtl number	[-]
q	heat flux,	[W/m^2]
Re	Reynolds number	[-]
T	temperature,	[°C]
V	velocity	[m/s]
y	period length of twisted tape	[mm]
w	width pf twisted tape	[mm]

Subscripts

b	bulk fluid temp.
f	fluid
in	inlet
out	outlet
nf	nanofluid
np	nanoparticle
s	smooth tube
w	water

Greek symbols

φ	volume fraction	(%)
ρ	density,	[kg/m^3]
μ	viscosity,	[kg/ms]
δ	thickness of twisted tape	[mm]

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