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Thermal Performance of Solar Parabolic Trough Collector Using Nanofluids and the Absorber with Nail Twisted Tapes Inserts

K. Syed Jafar*1 and B. Sivaraman*

Abstract – Experimental investigation was carried out to study the impact of absorber device with nail twisted tape of two different twist ratios of y = 2.0, and 3.0 and using Al_2O_3 / water nanofluid as the working fluid at 0.1%, and 0.3% particle volume concentration on the heat Transfer and friction factor characteristics of a solar parabolic trough collector. The tests are performed in the laminar range 710-2130 using indoor simulation under constant heat flux conditions. It is observed that the nail twisted tape absorber with nanofluids can significantly improve the heat transfer performance of the solar trough collector. The friction factor increases with twisted tape absorber due to swirl flow and over particle volume concentration and this is due to the increased nanofluid viscosity while increasing particle volume concentration. This result is useful for the design of absorber for solar parabolic trough collector.

Keywords – Friction factor, heat transfer, nanofluids, parabolic trough collector, twisted tape.

1. INTRODUCTION

Solar technologies can be used for a variety of applications such as electricity generation, steam generation, and some air cooling systems. Parabolic trough has obtained wide popularity in the solar technologies. Researchers have tested several types of heat transfer fluids in the PTC Solar collector, *e.g.*, mineral oils, silicones, heavy aromatic oils, and molten salts. Parabolic-trough solar water heating systems have shown that they achieve quite reasonable efficiency in converting solar radiation into useful heat of a heat transfer fluid [1], [2]. Odeh *et al.*, [3] proposed synthetic oil as heat transfer fluid in order to improve performance of collector Mahindersingh and Sulaiman [4] evaluated the long-term performance of the cylindrical parabolic trough concentrator. Valan Arasu and Sornakumar [5] have reported a newly developed the fiberglass reinforced parabolic collector. Reddy and Satyanarayana [6] have developed a numerical model of the porous fin receiver of the solar trough concentrator to enhance heat transfer. The concept of nanofluids was first materialized by Choi [7]. A series of research works at Argonne National Laboratory of USA which performed that the conventional liquid thermal performance could be remarkably improved using nanoparticles. Kihm *et al.* [8] proposed a theoretical nanofluid thermal conductivity model incorporating both nano particle heat dissipation as well as coagulation effect of the brownian. Natarajan and Sathish [9] have investigated the thermal conductivity enhancement of base fluids using nanotubes as a heat transport medium; it increases the efficiency of the solar water heater. Yousefi *et al.* [10] experimentally investigated the effect of MWCNT-H_2O nanofluid on the efficiency of flat-plate solar collectors and the result showed that using the MWCNT nanofluid without surfactant decreases the efficiency and with surfactant increase efficiency of collector. Many studies have been conducted on heat exchanger to enhance heat transfer augmentation or intensification by active and passive techniques.

Twisted tape is one of the most important members of enhancement techniques, which is employed extensively in heat exchangers. Many active and passive techniques are available for augmentation. Bergles [11] presented a comprehensive survey on heat transfer enhancement by various techniques. Eiamsa [12] has worked alternate clockwise and counter clockwise twisted tape inserts, for which heat transfer rate of the C–CC tapes increases with the decrease of twist ratio and the increase of twist angle values. Saha [13] tested integral helical rib roughness and with helical screw-tape insert and reported that the later are better than the individual enhancement technique, acting alone for laminar flow through a circular duct up to a certain value of fin parameter. A detailed survey of various techniques to augment the convective heat transfer is given by Kumar and Murugesan [14]. The thermal performance solar water heater with twisted tapes absorber surface has been reported by Kumar and Prasad [15]. Lin Lu *et al*. [16], applied CuO/water nanofluid in a high-temperature evacuated tubular solar collector and reported the heat transfer coefficients increases over particle volume concentration. Kasaeian *et al*. [17], numerically studied heat transfer behaviour of Al_2O_3-synthetic oil nanofluid in a trough collector tube with a uniform heat flux. It was found that Nusselt number and the convection heat transfer coefficients have direct dependency on the volume fraction of the nanofluid. Mukesh Kumar *et al*. [18], reported the heat transfer and friction factor characteristics of Al_2O_3/water nanofluid in a helically coiled tube heat exchanger under laminar flow. It is observed that the presence of nanoparticles further intensify the formation of secondary flow and proper mixing of fluid when nanofluid passes through the helically coiled tube. Khullar *et al*. [19] investigated theoretically a nanofluid-based concentrating parabolic solar collector. It was found that the thermal efficiency

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compared to a conventional parabolic solar collector is about 5–10% higher under the same weather conditions.

Risi *et al.* [20] reported that the performance of solar transparent parabolic trough collector working with gas based with CuO and Ni nanofluids. The maximum thermal efficiency of 62.5% for a nanofluid with an out let temperature of 650oC at 0.3% volume concentration was reported.

Nasrin and Alim [21] investigated numerically the flow and heat transfer phenomena of different nanofluids, compared their performances inside a solar collector, and reported that the Ag/water nanofluid are to be more effective in enhancing performance of heat transfer rate than that of CuO/water nanofluid. LalKundan and Sharma [22] have investigated the CuO-water based Nanofluid in the solar collector, it increases efficiency compared to water. Farajollahi *et al*. [23] observed the Brownian motion occur when volume concentration is more than optimum value of 2%. Therefore, it is expected that the heat transfer coefficient may decrease when the particle volume concentration is more than the optimum value. Suresh *et al*. [24] also reported that the nano particles suspended in water increases the Nusselt number even for a very low volume concentration of 0.3%. In this study 0.1 and 0.3% volume concentration of nano fluid were investigated and compared with water.

In the above researches, few studies were carried out for solar heating system using nanofluid in turbulent regime. Their results indicated a small decrease of the wall temperature on the heating absorber surface can cause a great increase of the absorbing solar energy in the solar collector. In the present work the experimental heat transfer and pressure drop results of the nanofluids (water and Al_2O_3) passing through the receiver with nail twisted tape of PTC collector under laminar flow conditions are presented.

.2. EXPERIMENTAL SET-UP AND PROCEDURE

The schematic of the experimental setup is shown in Figure 1. The experimental system mainly consisted of a test section, rota meter, a power source, a pump unit and a cooling water circulation system with chiller. The test section is copper tube with the dimension 2000 mm long with 12 mm diameter like the absorber tube of PTC solar collector. The copper tube is wound with ceramic beads coated electrical SWG Nichrome heating wire of resistance 37 ohms per meter length and maximum rating 1000W. Over the electrical winding, two layers of asbestos rope tape is wound. Over the asbestos tape winding approximately 50 mm thickness of glass wool is lined and over which, another two layers of asbestos rope tape is wound to minimize heat loss. The terminals of the Nicrome wire are connected to an autotransformer, regulating the heat flux. In the present indoor experiment, the absorber was heated with constant heat flux boundary condition by electrical wire surrounding at the absorber circumference instead of solar energy. The Auto-transformer is connected to the servo voltage regulator to minimize the voltage fluctuations. Calibrated RTD PT 100 type temperature sensors of 0.1°C accuracy with digital indicator are placed to measure the outside wall temperatures of absorber tube. The fluid mass flow rate was measured by a rotameter. Isothermal pressure drops were measured by a U tube manometer.

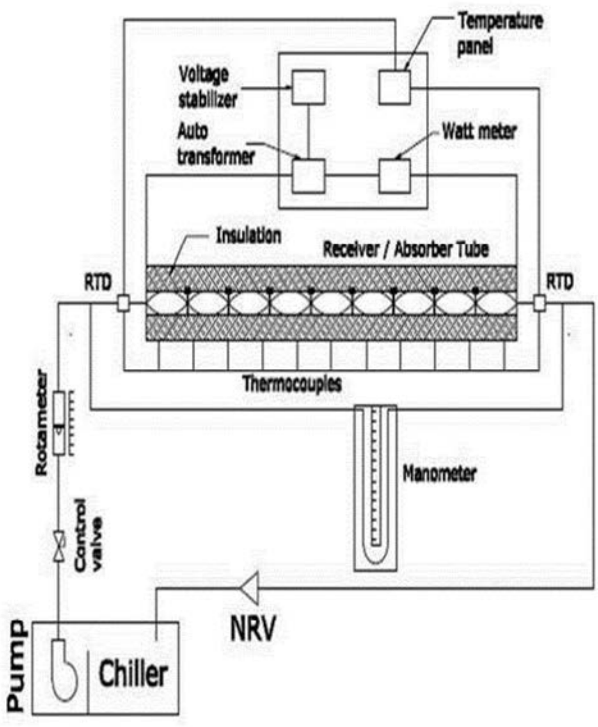

Fig. 1. Experimental setup.

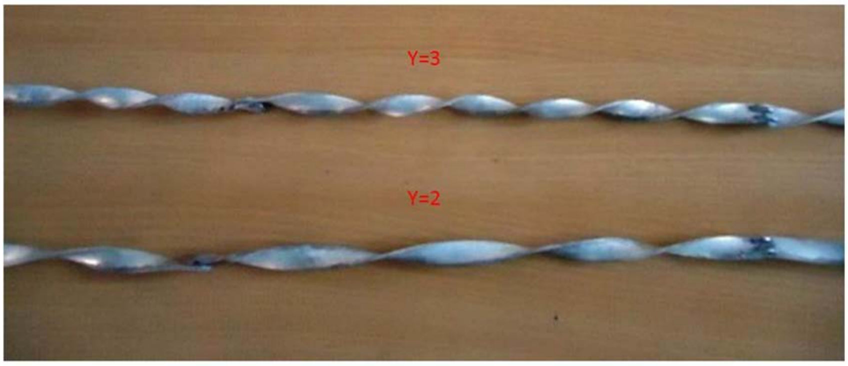

Fig. 2. (a) Plain Twisted Tapes (P-TT).

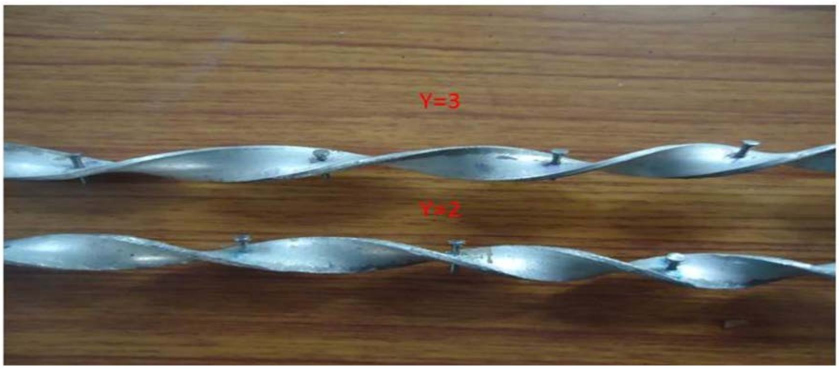

Fig. 2. (b) Nail Twist Tapes (N-TT).

Figure 2 (a) shows the twisted tapes are made of aluminium and have tape width (w) of 11 mm; tape thickness (t) of 1.5 mm and tape length (l) of 2000 mm. Nail (d_n=1.5mm, l_n=11 mm, h_{dn}=3 mm) twisted tape was obtained by punching small holes and carefully inserting nails on plain twisted tapes as shown in Figure 2(b). The nail twisted tape differs from the configurations already available in the literature. This shows that the turbulence is improved by augmentation of heat transfer characterizes of the absorber by introducing a nail tape in the absorber. The strips were twisted in the torsional twisting machine to the desire twisting ratio, about it's longitudinal axis, while being held under tension. In the experiment the fluid from the storage tank is pumped through the test section to the suction side of the reservoir. The temperature in the test liquid reservoir was maintained constant by circulating chiller water through the cooling tower. The heat flux was regulated with the help of Autotransformer, and the constant heat flux was allowed to continue till the steady state is attained. The inlet, outlet temperature of water, and the wall temperatures were noted after the steady state has been reached. The electrical heat flux was measured using a calibrated Ammeter and Voltmeter, and also with the help of Watt meter. The flow rate to the test section and heat flux was varied, and readings were taken after steady state. In this study, deionized water and water based Al_2O_3 nanoparticles at different volume concentration 0.1 and 0.3 % were used as the working fluid.

Al_2O_3 nanoparticles were commercial products made by the dispersing a specified amount of Al_2O_3 nanoparticles in water using an ultrasonic water bath (Toshiba, India) generating ultrasonic pulses of 100 W at 36±3 kHz. To get a uniform dispersion and stable suspension, which determine the final properties of nanofluids, the nanofluids are kept under ultrasonic vibration continuously for 6 hours.

3. DATA REDUCTION

3.1 Thermophysical Properties of Nanofluids

The thermo-physical properties of nanofluids such as specific heat and density at different concentrations are calculated from Choi and Eastman [25] using proposed the Eqs. (1), (2) as:

$$(\rho c_p)_{nf} = \phi(\rho_p\ c_{p,p}) + \rho_w\ (1-\phi) c_{p.w} \quad (1)$$

$$\rho_{nf} = \phi\rho_p + (1-\phi)\rho_w \quad (2)$$

The effective thermal conductivity of dilute nanofluids (k_{nf}) can also be evaluated using the Maxwell model for nanofluids with volume fraction less than unity. Maxwell equation is given by,

$$\frac{k_{nf}}{k} = \frac{k_s + 2k + 2\phi\,(k_s - k)}{k_s + 2k - \phi\,(k_s - k)} \tag{3}$$

3.2 *Heat Transfer Calculation*

The heat flux supplied of the absorber section and energy absorbed by the flowing fluid is calculated from Eqs. (4) and (5).

$$q = V \times I \tag{4}$$

where V is the voltage and I is the current.

$$q = m\,c_p\,(T_{out} - T_{in}) \tag{5}$$

The average heat transfer coefficient was obtained from,

$$h = \frac{q''}{\left(\overline{T}_w - \overline{T}_b\right)} \tag{6}$$

where $\overline{T}_w$ and $\overline{T}_b$ are the mean wall and bulk fluid temperatures Where, T_{wall} is the local wall temperature evaluated at outer wall surface of tube.

$$\overline{T}_w = \frac{\sum T_w}{11}$$

The Nusselt Number can also be determined from the well-known shah equation for laminar flow under constant heat flux boundary conditions is in reasonable agreement:

$$Nu = 1.953\left(\mathrm{Re}\,\mathrm{Pr}\,\frac{d}{x}\right)^{\frac{1}{3}} \quad for \left(\mathrm{Re}\,\mathrm{Pr}\,\frac{d}{x}\right) \geq 33.33 \tag{7}$$

The average Nusselt number is calculated as

$$\mathrm{Nu} = \frac{h\,D_i}{k} \tag{8}$$

The Reynolds number is given by

$$\mathrm{Re} = \frac{\rho V D i}{\mu} \tag{9}$$

3.3 *Pressure Drop Calculation*

The pressure drop (Δp) measured across the test section under isothermal condition is used to determine the friction factor (f) using the following relation

$$f = \frac{\Delta p}{\frac{1}{2}\rho v^2}\,\frac{D}{L} \tag{10}$$

4 RESULTS AND DISCUSSION

4.1 *Validation of Experimental Results*

The present experimental results were validated by performing experiments using pure water and comparing the results obtained with previous correlations under similar conditions. Figure 3 shows laminar flow, isothermal friction factor (Moody, 1944) for the plain tube compared with analytical equation, $f = 64/R_e$ (both f and Re defined on the basis of hydraulic diameter) and Nusselt number data.

Figure 4 shows the variation of the Nusselt number with Reynolds number for the plain tube. The data obtained by the experiment are matching with the shah equation of standard correlations for plain tube. The data agreed within ±14% and ±13%, respectively, for the friction factor and the Nusselt number.

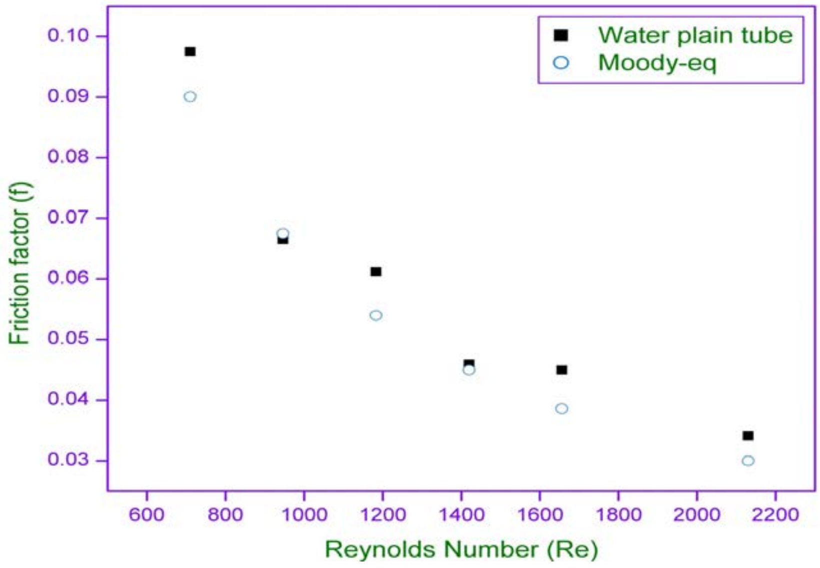

Fig. 3. Data verification of plain tube friction factor.

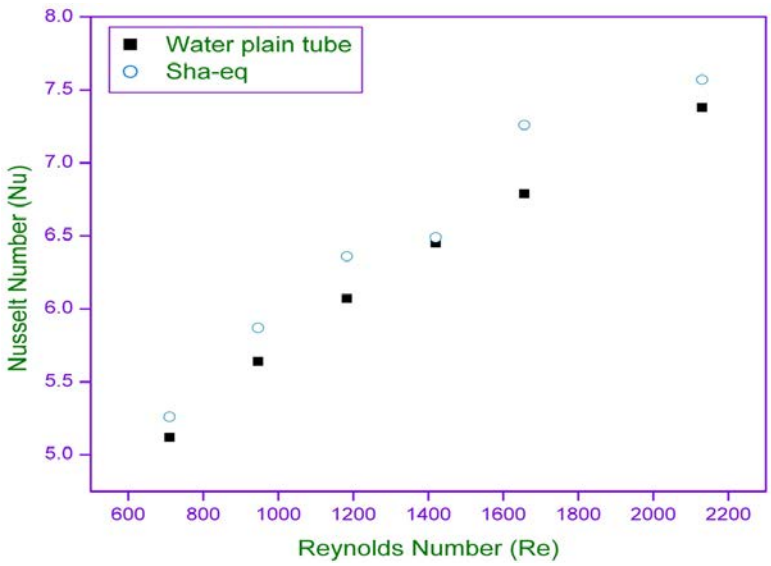

Fig. 4. Data verification of plain tube Nusselt number.

4.2. Heat Transfer Performances and Pressure Drop Characteristics

The experimental Nusselt number of water and different volume concentration nanofluid in a plain tube with twisted tape inserts is shown in Figures 5 and 6 respectively.

It can be observed that Nusselt number considerably increases with increasing Reynolds number. From the experimental results, it is clear that the twisted tape inserts caused swirl and pressure gradient in the radial direction.

In addition, the heat rate is significant than that due to the presence of nano particles, resulting in a better mixing between the core fluid and tube wall. It can also be observed that the heat transfer enhancement becomes significant with a decreasing twist ratio of twisted tapes.

The experimental results also reveal that the nail twisted tape (N-TT) results in a higher Nusselt number than plain twisted tape (P-TT). This can be attributed to the fact that the nails act as turbulator and gives intensive mixing of nano fluid that promotes the turbulence near the tube wall surface that break the boundary layer at the surface which enhance the heat transfer and pressure gradient might be created along the radial direction while the P-TT causes swirl flow only. In addition, the simultaneous use of the N-TT and nanofluid considered in the present experimental lead to further heat transfer enhancement, increase of pressure drop and hence increase in pumping power.

The reason for higher pressure drop was the dissipation of dynamic pressure of the fluid due to high viscosity loss near the tube wall. Throughout the experimental results, It is obvious that nanofluid of 0.3% volume concentration with nail twisted tape the nail twisted tape (y=2) yielded the higher volumes of heat transfer compared to other data. This can be due to increase of shear force on tube wall acted by a larger number of nanoparticles. The maximum increase in the Nusselt number was observed to be around 16% when nanofluid with 0.3% volume concentration. is used compared with distilled water in a plain tube. The maximum enhancement in Nusselt number is about 20% when nanofluid with 0.3% volume concentration is used with nail twisted tape tube.

The experimental friction factor of water and different volume concentration nanofluid in a plain tube with twisted tape inserts is shown in Figure 7 and 8, respectively. The experimental results show that the friction factor significantly increases with increasing concentration of nano particles. It is clear that the use of nanofluid and inserts results in a very high friction factor than that of a plain tube. The effect nail twisted tape with nano fluids (0.3%).

Volume concentration increases the surface areas that affect considerably the pressure losses of fluid flow due to the increase of the disturbance in the laminar layer of the boundary layer.

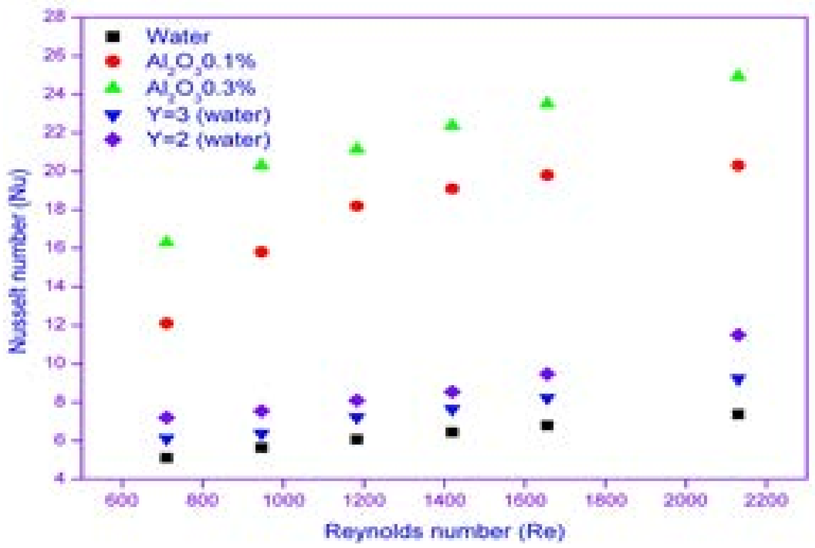

Fig. 5. Variation of Nusselt number with Reynolds number for water and nanofluid in plain tube and plain twisted tape.

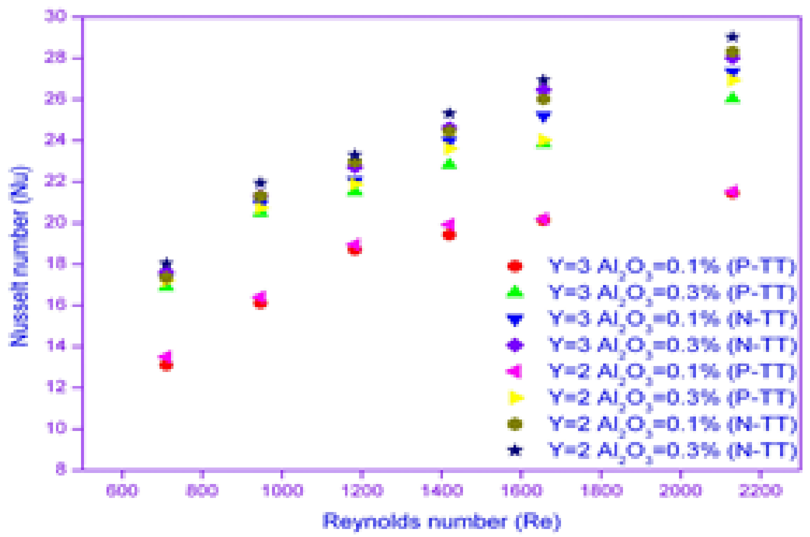

Fig. 6. Variation of Nusselt number with Reynolds number for water and nanofluid in plain tube and with various twisted tapes.

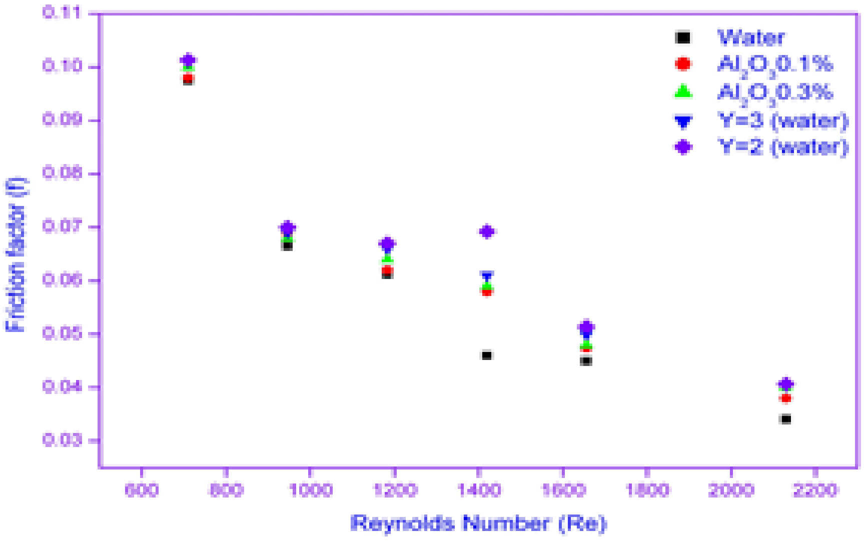

Fig. 7. Variation of friction factor with Reynolds number for water and nanofluid in plain tube and plain twisted tape.

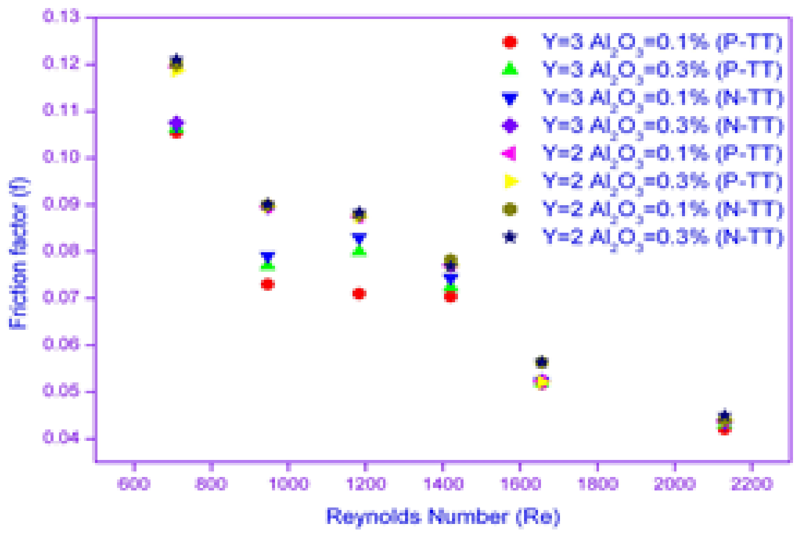

Fig. 8. Variation of friction factor with Reynolds number for water and nanofluid in plain tube and with various twisted tapes.

5. CONCLUSION

Heat transfer and friction factor characteristics of experimental research was carried out to investigate in receiver/absorber under laminar flow regime using Al_2O_3 / water nanofluids as the working fluids with two different concentrations of 0.1% and 0.3% with nail twisted tape and plain twisted tape inserted. The experimental results lead to the following conclusions.

1) Nusselt Number considerably increases with increase in nanofluid concentration.
2) At same conditions, heat transfer rate further increased due to twisted tapes and nanofluid.
3) The use of nanofluid enhances the heat transfer coefficient in the range tested with no significant enhancement in pressure drop compared to water. The twisted tape inserts result in pressure drop due to the interaction of the pressure forces with inertial forces in the boundary layer.

The major findings of this experimental investigation are that the use of nanofluid (0.3%) with nail twisted tapes (N-TT) yields higher Nusselt Number and high friction factor.

NOMENCLATURE

A	Surface area, m^2
Cp	Specific heat capacity, J/kg K
D	Diameter of copper tube, m
d_n	Diameter of nail
f	Friction factor

h	Convective heat transfer co-efficient, W/m^2K
h_{dn}	Head diameter of nail
I	Current (A)
k	Thermal conductivity, W/m K
l_n	Length of nail
m	Mass flow rate, kg/s
Nu	Nusselt number
Q	Heat transfer rate, W
q	Heat input, W
q″	Heat flux, W/m^2
Re	Reynolds number
T	Temperature, K
V	Voltage, (V)

Greek symbols

ρ	Density, kg/m^3
φ	Particle volume concentration (%)
μ	Dynamic Viscosity (kg/m^2·S)

Subscripts

f	Base fluid
n_f	Nanofluids
p	Particle
W	Water

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