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PERFORMANCE CHARACTERISTICS OF PARABOLIC SOLAR COLLECTOR WATER HEATER SYSTEM FITTED WITH NAIL TWISTED TAPES ABSORBER

K. SYED JAFAR*, B. SIVARAMAN

Department of Mechanical Engineering, Annamalai University,
Annamalainagar - 608002,Tamil Nadu, India
*Corresponding Author: majallelku@gmail.com

Abstract

In this paper, the experimental heat transfer, friction loss and thermal performance data for water flowing through the absorber tube fitted with two different twisted tape configurations in parabolic trough collector (PTC) are presented. In the present work, a relative experimental study is carried out to investigate the performance of a PTC influenced by heat transfer through fluid-absorber wall mixing mechanism. The major findings of this experiment show that heat transport enhancement in the nail twisted tape collector perform significantly better than plain twisted tapes and also show that the smallest twisted tape ratio enhances the system performance remarkably maximizing the collector efficiency. The results suggest that the twisted tape and nail twisted tape would be a better option for high thermal energy collection in laminar region of the PTC system.

Keywords: Solar parabolic trough collector, Heat transfer, Friction factor, Twisted tape.

1. Introduction

Solar water heating is being used to reduce the amount of water that must be heated by a direct conventional water-heating system, substituting renewable energy for electricity or fossil-fuel. Solar parabolic trough collectors (PTCs) are used for a variety of applications such as heating, cooling, drying and power generation. Solar water heating system is becoming more effective due to considerable research. Hot water generation system has two main parts: a solar collector and a storage tank. Solar-trough collectors use a parabola shaped reflector assembly to concentrate sun radiation onto an absorber tube located along the focal line of the mirrors assembly. The pressurized circulating tube through which the working fluid circulates is coated with a special high absorptance

Nomenclatures

A	Surface area, m^2
A_a	Collector aperture area, m^2
C_p	Specific heat capacity, J/kg K
D_i	Inside diameter of absorber tube, m
F_R	Collector heat removal factor
f	Friction factor
h	Convective heat transfer co-efficient, W/m^{2}K
H	Pitch for 180^0 rotation of twisted tape, m
I	Incident Solar beam Radiation, W/m^2
k_w	Thermal conductivity of the absorber tube wall, W/m K
L	Length of Collector, m
$\dot{m}$	Mass flow rate, kg/s
Nu	Nusselt number
Q	Useful heat gain, W
Re	Reynolds number
T	Temperature, K
u_m	Bulk mean fluid velocity m/sec.
U_O	Overall heat loss coefficient, W/m^2 K
W	Width of twisted tape, m
Y	Twist ratio (H/W)

Greek Symbols

ΔP	Pressure drop, N/m^2
η	Collector efficiency, %
μ	Dynamic viscosity, kg/ms
ρ	Density, kg/m^3

and low emittance surface and is enclosed in a glass tube. The temperature of the transfer fluid in the PTC systems rises to as much as 271°C or even more, but for large scale hot water supply systems typically operate at about 93°C to deliver water at about 49-60°C. Efficiency is the highest with a temperature difference of about 33°C between input to the solar collector system and output from the field to the thermal storage tank. Al-Madani [1] investigated the performance of a low cost solar water heating system by a cylindrical design and compared it with the flat plate collector.

Shukla et al. [2] reviewed exclusively the design aspects of the solar water heating systems. Kalogirou [3] studied the design and performance characteristics of a parabolic trough concentrator. Odeh and Morrison [4] developed a transient simulation model to establish a storage tank design which enables the transient performance of a solar industrial water heating system. Arasu and Sorrnakumar [5] carried out the design procedure of fiberglass reinforced reflector assembly for parabolic trough solar collector.

Kumaresan et al. [6] investigated the performance of a solar PTC integrated with a storage tank capable of storing the heat during day. Mokhtari et al. [7] carried out optical performance tests to improve the optical efficiency of the PTC using the thermal hot oil as heat transfer fluid generation system. Reddy and Satyanarayana [8] developed a numerical model for predicting the performance of the absorber with different configurations of porous inserts. Among the trapezoidal porous inserts, that with a strong tip base thickness was more effective on the thermal fluid characteristics of PTC receiver. Al-Ansaryl and Zeitoun [9] carried out a numerical study on a half-insulated air-filled annulus of the receiver of a PTC to significantly improve its performance.

Hegazy [10] derived the heat balance equations for net heat energies absorbed by the externally finned absorber and envelope of a parabolic trough solar collector. One possibility of improving the performance of convective heat transfer system is by enhancing passively the surface geometries of twisted tapes. Bergles et al. [11] have reported a comprehensive survey on augmentation of heat transfer. Chang and Guo [12] have investigated the heat transfer properties over developing and developed flow regimes with spiky twist tapes. Among these comparative groups, the present V-notched spiky twisted tape has obtained the highest heat transfer enhancement impacts with favorable thermal performance factors. Eiamsa-ard et al. [13] investigated the results of the heat transfer and pressure drop characteristics in a tube, using twisted tapes with alternate axes at different alternate lengths. Based on the experimental results, a better enhancement effect of decreasing the alternate lengths typical twisted tapes was found. Bas and Ozceyhan [14] reported the heat transfer and pressure drop characteristics of a circular tube fitted with a twisted tape placed separately from the tube wall to yields heat transfer rate increase depending on the laminar sub layer destruction near the tube wall.

Al-Fahed et al. [15] carried out experimental studies on heat transfer and compared both micro tube and twisted tape inserts in laminar flow. Kumar and Prasad [16] investigated twisted tape inserted solar water heaters to enhance convective heat transfer. Jaisankar et al. [17] investigated the effects of the helical twisted tape on heat transfer and flow friction characteristics of forced circulation in solar water heater system. García et al. [18] carried out an experimental study on heat transfer of flat-plate solar water heater fitted with wire-coil insert. It is found that wire coils have significant effect on the heat transfer and pressure drop augmentations. Vipin et al. [19] attempted to review various heat transfer enhancement in the solar thermal system. It is found that superior enhancement in the heat transfer was achieved with little penalty of friction. Passive augmentation techniques such as twisted tape swirl generator inserts in the absorber of the parabolic trough solar collector hot water generations system improve heat transfer and thermal performance. Since a very limited work has been reported on twisted tapes in parabolic trough solar collector system, this study focuses on twisted tape inserts in the absorber of PTC system to improve the performance.

2. Experimental Setup

An experiment prototype PTC was developed to investigate heat transfer, friction factor and thermal performance of the collector having an absorber fitted with a nail twisted tape in a real time outdoor condition. The schematic diagram of the experimental setup with a twisted tape absorber PTC collector system is shown in Fig. 1. The collector unit comprises a reflective surface of the trough, the solar radiation absorption system, microprocessor based electro mechanical tracking system, a storage tank, a circulating pump, a flow meter and other controlling devices. The photographic view of the PTC system used for experimental investigation is shown in Fig. 2. The concentrator of the trough collector with a rim angle of 90° is very accurately made of steel. The receiver, which is placed along the focus line of the concentrator, consists of a black coated copper tube coated with black paint, and is covered by a glass envelope for minimizing thermal heat losses through convection and conduction. The main function of the absorber of a PTC is to absorb the focused solar radiation and transfer the concentrated radiation to the working fluid flowing through its tube. A pump circulates water from a collecting tank through the absorber tube of the solar system and back to the collecting tank. The hot water supply tank and circulation pipe lines are insulated with glass wool. The PTC is oriented with a tracking north-south axis.

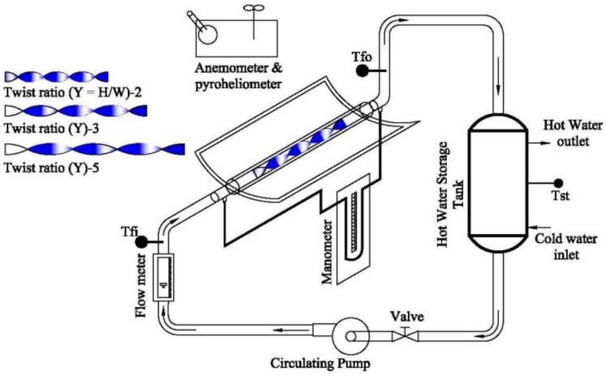

Fig. 1.The Schematic diagram of the experimental setup.

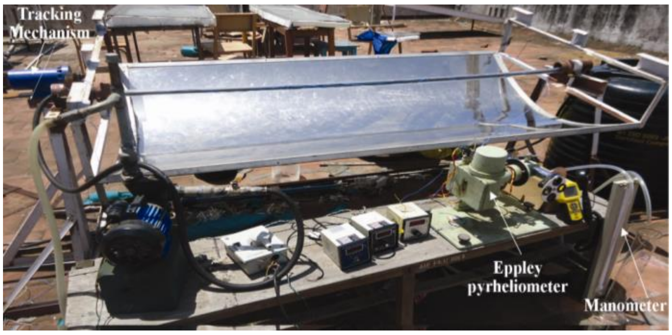

Fig. 2.Photographic view of the experiment platform.

The collecting tank is filled (up to half) from the main water supply. The water temperatures at the inlet and outlet of the absorber tube, water flow rate, and solar radiation intensity have been continuously measured during the experiment. Two calibrated RTD PT 100 type temperature sensors have been used to measure various temperatures of water at inlet and exit of the absorber with a digital temperature indicator of 0.1 °C accuracy. A rotameter has been used to measure the fluid mass flow rate with an accuracy of ±1 %. Isothermal pressure drop was measured by using a U tube manometer between two ends of the tube section. An Eppley Pyrheliometer has been used to measure the solar radiation intensity and its precision can be controlled within 2 %. The reflector surface was made of a highly solar reflective material of reflectance 0.974, a special black painted copper tube of absorptance 0.97 was tested by a double beam spectro photometer at Central Electrochemical Research Institute, Karaikudi, Tamil Nadu, India. The PTC specifications of the system are given in Table 1.

Table 1.Solar PTC Specifications.

Parameter/Feature	Value
Aperture length (*L*)	2 m
Aperture width (*W*)	1 m
Focal point distance (*F*)	0.25 m
Receiver tube internal diameter ($D_{r,\ int}$)	12 mm
Receiver tube external diameter ($D_{r,\ ext}$)	12.5 mm
Envelope cover internal diameter ($D_{c,\ int}$)	18 mm
Envelope cover external diameter ($D_{c,\ ext}$)	22 mm
Concentration ratio (*C*)	25.46
Receiver tube absorptance (α)	0.97
Absorber tube emissivity (ε_a)	0.25
Envelope tube emissivity (ε_e)	0.94
Tracking mechanism type	Electronic

The plain twists used in the study were made up of thin, 1.5 mm flat strip of aluminum. It was 11 mm in width and 2000 mm in length. Nail- twisted tapes were made by punching small holes and properly inserting nails on along the plain twisted tapes. These uniform and identical nails are of 11mm height (equal to tape width) to maintain the tape-absorber radial spacing thus not reducing the radial heat transfer. The nail twisted tape differs from the geometries already available in the literature [20, 21]. The strips were twisted in the torsional twisting machine to the desired twisting ratio and were later inserted in the absorber of the PTC system. Figure 3 shows the photograph of plain twisted tape and nail with twisted tape used in the experiments.

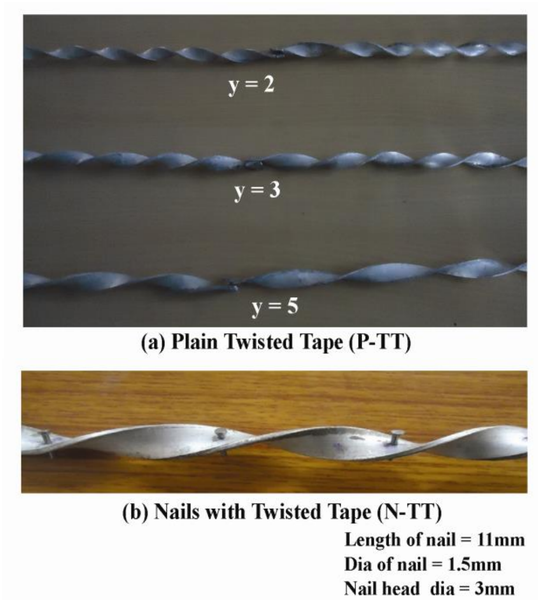

Fig. 3. Geometries twisted tapes.

3. Experimentation and Data Collection

Experiments were conducted at an open area of the Solar Energy Laboratory, Annamalai University, Annamalainagar (longitude 79.7161°E, latitude 11.3967° N). The collector was tested during the months of March to July 2014. The experimental part involved measurement of temperature and pressure drop measurements of fluid flow in an absorber of a solar PTC. The characteristics of the absorber fitted with inserts consisting nails (N-TT) and plain twisted tapes (P-TT) with three different twist ratios (*Y* = 2, 3, and 5) were tested under outdoor conditions. The experiments are conducted on various days from 10.00 to 13.00 h during which mean solar beam radiation varied between 350-780 W/m^2 and the mean ambient temperature varied between 33-37^{o}C. Experiments were conducted using the water as the working fluid with Reynolds number ranging between 710-2130. Seven K-type thermocouples were embedded along the outer wall of absorber tube for measuring its local temperatures during operation. Axial locations of thermocouples were 0.04 m, 0.45 m, 0.9 m, 1.3 m, 1.6 m, 1.75 m and 1.95 m, respectively.

4.Data Analysis

In the experiments conducted, the PTC was installed in a location with access to sunlight, and throughout the experiment, the collector was kept with its absorber tracking the beam radiation continuously so as to maximize the use of radiant energy. Water in the test tube received rate of useful energy (Q) from the solar radiation mainly via the convective heat transfer mechanism. Thereby, Q was assumed to be equal to the convective heat transfer within the test tube and can be expressed as

$$Q = \dot{m}C_p(T_o - T_i) = U_o A_o (T_{wo} - T_m) \tag{1}$$

The overall heat transfer coefficient can be estimated from the steady state equation

$$\frac{1}{(U_o A_o)} = \frac{1}{(h_1 A_1)} + \ln(D_o / D_i)/(2\pi K_w L) \tag{2}$$

The heat transfer performance was defined in terms of the Nusselt number (Nu) and the maximum possible average value of the heat absorbed by a fluid taken for internal convective heat transfer coefficient (hi) given by

$$\text{Nu} = hD_i / k \tag{3}$$

In the present work, the pressure drop across the absorber loss is represented non-dimensionally a friction factor. It was estimated under isothermal flow conditions using the following definition:

$$f = \frac{2\Delta p}{\rho u^2}\frac{D_i}{L} \tag{4}$$

where, ∆P is the pressure across the absorber section, D_i is the inner diameter of tube, *u* is the velocity of water, and L is the length of the tube.

The Reynolds number is given by

$$\text{Re} = \frac{\rho u_m D_i}{\mu} \tag{5}$$

Instantaneous efficiency

The efficiency of the PTC System is determined by dividing the energy absorbed by the working fluid as it passes through the absorber, by the solar energy falling on the collector aperture. This can be expressed as follows:

$$\eta_c = \left[\frac{(T_o - T_i).\dot{m}.c_p}{I \times A_a} \right] \quad (6)$$

5. Results and Discussion

The experimental values for Nusselt number and friction factor were evaluated by conducting experiments in a plain tube with water at different Reynolds numbers. Experimental data were validated by comparing the present friction factor with those obtained from the Hagen-Poiseuille equation data in Fig. 4, the present Nusselt number with those calculated from the Sieder-Tate equation in Fig. 5, the standard correlations for plain tube. The data fall within ±12% and ±15%, deviation, respectively, for the friction factor and the Nusselt number. It has been observed that the Nusselt number increases with an increase in the Reynolds number. This means that the intensity of solar radiation increases gradually which maximizes the fluid flow as a result of increased turbulence intensity.

5.1. Effect of twist tapes on heat transfer analysis

The influence of plain twisted tapes (P-TT) and modified nail twisted tapes on Nusselt number is also shown in Fig. 6. Compared to the plain tube, the tube with twisted tapes and nail twisted tapes exhibit higher Nusselt number, because of the tape decreasing the hydraulic diameter and it increases with extra swirl motion to generate swirl flow through the tube and better fluid mixing, resulting in a more efficient destruction of the thermal boundary layer and thus better heat transfer between the core and absorber tube wall continues for a prolonged period. The swirl enhanced the flow turbulence that led to even better convection heat transfer.

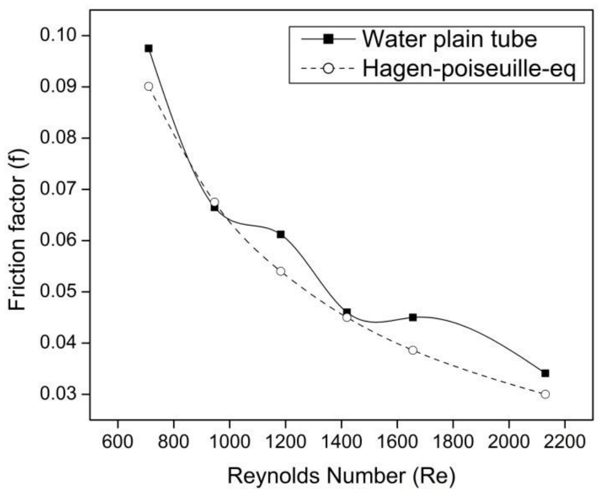

Fig. 4. Data verification of plain tube fraction factor.

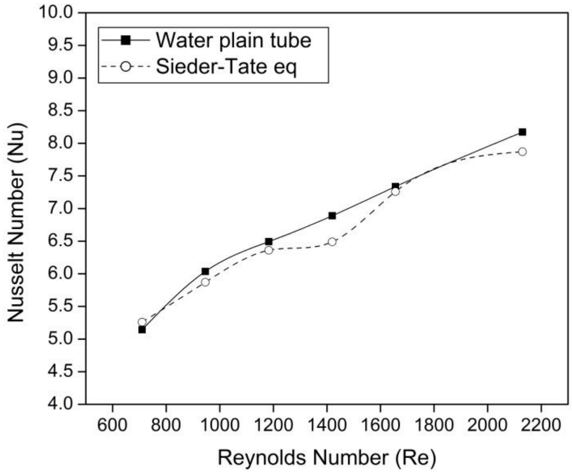

Fig. 5. Data verification of plain tube Nusselt number.

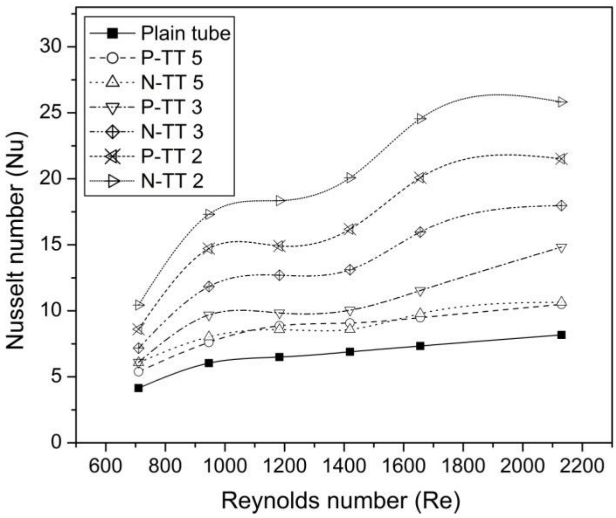

Fig. 6. Variation of Nusselt number with Reynolds number for plain and nail twisted of various twist ratios.

5.2. The system with various twist ratios

Comparing full system with various ratios (Y = 2, 3, 5) with minimum twist ratio induces the stronger swirl flow higher in thinner fluid boundary layer along the tube wall. The experimental results also reveal that the nail twisted tape (N-TT) provides a higher Nusselt number than the plain twisted tape (P-TT). This is due to the fact that fluids get extra turbulence as well as collision to be in contact positioned around tape through a nail side of the tape. The increase in the Nusselt number was observed to be around 10-15% when plain twisted tube (Y = 2) is used, compared with a plain tube. The similar behavior was observed for nail twist inserts. The increase in the Nusselt number from twist ratio 2 is nearly 20-30% for all Reynolds numbers.

This is due to the fact that in plain twisted tapes, there is only a swirling flow, where as there is vigorous fluid mixing phenomena due to flow separation, detachment and reattachment of the recirculation of fluid in the presence of the nails. Also, there is faster irregular abrupt flow movement path and the flow transport phenomenon was changed in both the molecular and bulk flow levels, causing additional pressure drop and faster heat transmission. This result is used at the different low operating temperature end of the heat transfer fluid loop in water heating system for the design of solar PTC.

5.3. Effect of twist tapes on friction factor analysis

The friction factor result is shown in Fig. 7. It shows the variation of friction factors with Reynolds number. The friction factor for twist tape absorber tube is higher than the plain tube. Apparently, friction factor increases with minimum twist ratio twisted tapes in absorber due to the high swirl generation. The friction factors of absorber tube fitted with minimum inserts are obtained as 10.12% and 9.01% when compared with plain tube at the Reynolds of 2130. As twist ratio increases, the swirl effect decreases and minimizes the friction factor and pressure drop. In addition, the nail twisted tape causes greater friction than plain twisted tapes due to increased wetted surface and fluid pressure. Moreover, the pressure loss had a high possibility to occur by the obstruction of the flow pressure forces with inertial forces in the boundary layer.

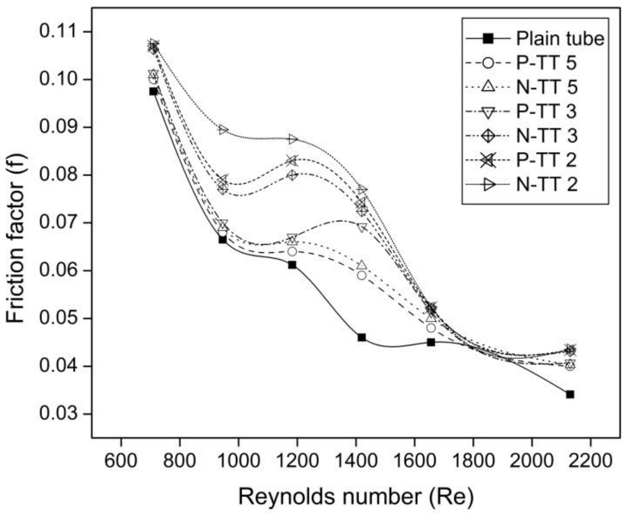

Fig. 7. Variation of friction factor with Reynolds number for plain and nail twisted of various twist ratios.

5.4. Effect of twist tapes on thermal performance analysis

The variation of instantaneous efficiency with solar radiation is illustrated in Fig. 8. As shown, the efficiency increases sharply as the solar radiation increases.

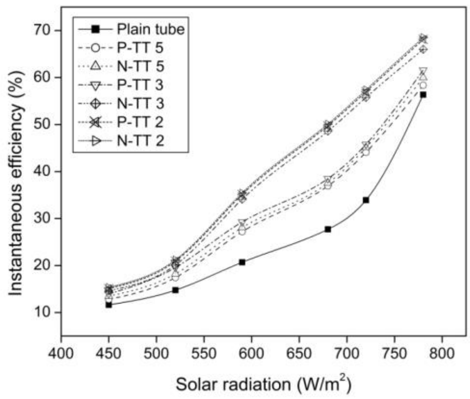

Fig. 8. Variation of efficiency with solar radiation for plain and nail twists of various twist ratios.

It is evident that such a situation for the given solar intensity, the efficiency of twisted tape absorber of PTC is always higher than the plain tube absorber; the results also show that the maximum efficiency is obtained with the minimum twist ratio. This is because of heat accumulation effects and stronger swirl flow generated when the fluid flows over the twisted tape of the absorber.

The use of nail twisted tape provides considerably higher efficiency than that of plain twisted tapes. The effect of the absorber tube temperature on the variation of solar radiation is shown in Fig. 9. It is observed that for various twist ratios, the lowest twist ratio decreases the lowest absorber tube temperature with an increase in the Reynolds number, that the heat loss decreases and the heat removal factor is improved. The thermal efficiency of a concentrating collector using the ASHRAE 1986 Standards operating under steady state conditions can be tested outdoors to rate the collectors. In Fig. 10 the thermal efficiency curve for PTC system of nail twisted tape (Y = 2) is presented. The experimental values are fit into a straight line by the least square fitting method. The intersection of the vertical efficiency axis is equals to $F_R\eta o$. The slope of the line is equal to F_RU_L/C. A comparison of intercept value with previous researchers is given in Table 2. It can be seen that a significant improvement in the efficiency of PTC system with nail twisted tape inserts is achieved.

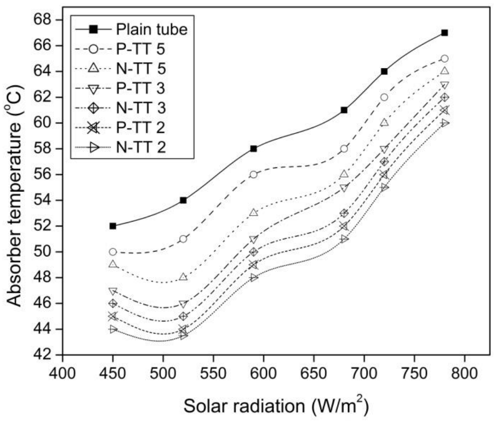

Fig. 9. Effect of average absorber temperature for plain and nail twists of various twist ratios.

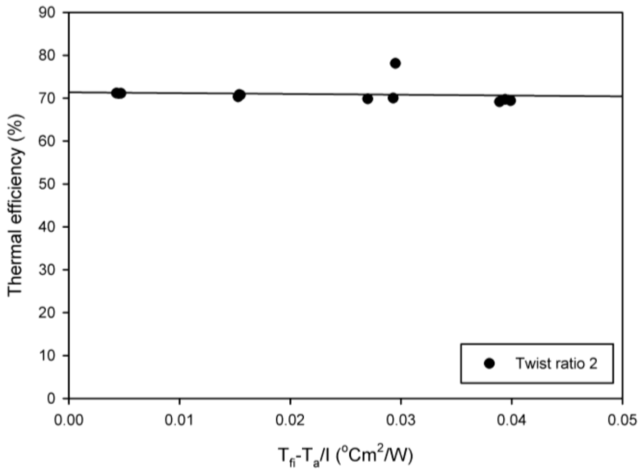

Fig. 10.Thermal efficiency curve.

Table 2 Comparison of collector efficiency equations.

Efficiency equation $\eta = F_R\eta_o - \frac{F_R U_L}{C}\left(\frac{T_{ft} - T_a}{I}\right)$	**References**
0.71- 0.2454(T_{fi} - T_a)/I	Present work
0.69-0.3865(T_{fi} - T_a)/I	Arasu and Sornakumar [5]
0.638-0.387(T_{fi} - T_a)/I	Kalogirou [3]

5.5. Correlations for Nusselt number and frictions factor

In this present investigation, response surface methodology (RSM) approach using central composite design was applied with full replication technique to develop an empirical relationship for predicting Nusselt number and friction factor. To develop an empirical relationship based mathematical model second order polynomial equation was used. The method to develop the equation, analysis of coefficients and significance of the predicted results is described in our previous publication [22]. Figures 11(a) and (b) show the predicted results of the Nusselt number and friction factor using the developed mathematical models (7) and (8) tested by ANOVA technique and compared with the experimental values. The average error between experimental and predicted values is ±2%. It is observed that there is an acceptable qualitative and quantitative conformity between predicted values by the experimental values.

$$\mathrm{N_u} = 9.83 + 1.21\mathrm{Re} - 1.42Y - 0.22\,\mathrm{Re}Y + 0.42\mathrm{Re}^2 - 0.24Y^2 \quad (7)$$

$$f = 0.067 - 0.011\mathrm{Re} - 2.249\times10^{-3}Y - 5.227\times10^{-4}\,\mathrm{Re}Y + 4.848\times10^{-3}\,\mathrm{Re}^2 - 1.902Y^2 \quad (8)$$

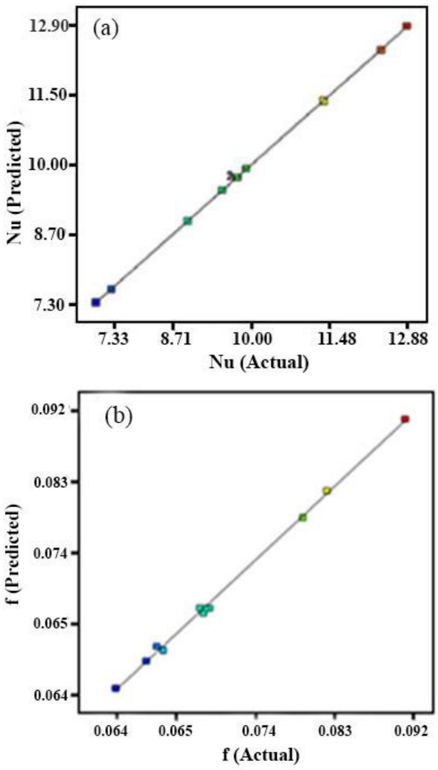

Fig. 11 (a) and (b). Correlation plots for Nusselt Number and Friction factor of the responses.

From the above figures and our previous discussions [22], it is implied that high correlation exists to a value of 99.9999% for Nu and 99.79 % for $f(R^2 = 0.9999$ for Nu and 0.9979 for f) between experimental and predicted results. Hence, the developed mathematical equations can be used to predict the considered responses.

6. Conclusions

Experimental investigation to evaluate the Nusselt and friction factor characteristics of a solar parabolic trough absorber by designing different twist ratio twisted tapes and nail twisted tape inserts have been done.

- The experimental data obtained are compared with those obtained from fundamental equations and found that they are in reasonable agreement.
- The minimum twisted tape inserts in the absorber increase the heat transfer characteristics with considerable pressure loss. The enhancement of heat transfer in nail twisted tape is found to be slightly higher than the plain twisted tape.
- The instantaneous efficiency of twisted tape absorber of PTC increases with the increase in solar intensity and with lowest twist ratio, due to heat loss from the twisted enhanced absorber by natural convection which was lower than that of the conventional absorber. An increase in instantaneous

efficiency of about 27% with nail twisted tape (Y = 2) as compared to the plain tube absorber has been obtained.

Hence it has been concluded that the nail twisted tape with absorber of PTC to show the clear enhancement of thermal performance.

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