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Experimental Analysis of Twisted Tape Configurations for Augmenting Heat Efficiency in Cylindrical Parabolic Solar Water Heater

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Abstract

This experimental study investigates the performance enhancement of a cylindrical parabolic concentrating solar water heater (CPCSWH) by using a twisted tape insert in the absorber tube.The flow and heat transfer characteristics were analysed for mass flow rates of water ranging from $\dot{m}$ = 0.0197–0.0527 kg/s, twist ratios (Y)= 1&2, and Reynolds numbers (Re) = 2574.46–6627.92. The results show that the twisted tape insert in the absorber tube of the CPCSWH improves the outlet water temperature, collector efficiency, and Nusselt number (Nu) compared to the CPCSWH without the insert. For a fixed mass flow rate of water, the outlet water temperature (T_o) and collector efficiency (η) increase with a decrease in the twist ratio and are higher for a lower twist ratio (Y = 1). The correlations between the Nusselt number and friction factor were developed based on the experimental data. The Nusselt number correlation shows a positive correlation n with the Reynolds number and the twist ratio, while the friction factor correlation exhibits an inverse relationship with the Reynolds number and the twist ratio. The study reveals that the use of a twisted tape insert in the absorber tube of a CPCSWH can significantly enhance its performance. The correlations developed in this study can aid in predicting the heat transfer and flow characteristics in CPCSWHs with twisted tape inserts. These findings can be useful in the design and optimization of CPCSWHs for various applications, including solar thermal power generation and space heating.

***Keywords**:* Collector efficiency,CPCSWH,friction factor,twist ratio,twisted tape

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I. INTRODUCTION

Solar energy stands out as a beacon of promise in the global pursuit of clean, reliable, and sustainable energy solutions. As the world grapples with the escalating demand for energy, the spotlight has increasingly turned to alternative sources, with solar energy emerging as a frontrunner. This renewable energy source harnesses the power of the sun to generate electricity and heat water, presenting itself as an abundant and eco-friendly solution to our energy needs.

Technological strides have propelled solar energy into the forefront of viable options for a diverse range of applications. The efficiency and cost-effectiveness of solar technologies have witnessed substantial improvements, rendering them practical for residential, commercial, and industrial utilization. This shift towards solar power aligns with a global movement towards cleaner and greener energy solutions, mitigating the environmental impact of conventional energy sources.

One noteworthy advancement in the solar energy sector is theCPCSWH. This technology promises to revolutionize the way we heat water by overcoming limitations associated with traditional flat plate collectors. The cylindrical design offers higher efficiency, cost-effectiveness, and enhanced performance even in low-light conditions. This innovation not only addresses the growing energy needs but also positions solar energy as a versatile and dependable source for water heating applications.

II. LITERATURE REVIEW

Jeter et al.[1]conducted a study on parabolic trough collectors, analysing geometrical factors' impact. They identified end effects, bulkhead shading, and intra-array shading as key contributors to reduced collector aperture. Formulas were developed to quantify the effects, aiding in better performance estimations by addressing these variables' influence on parabolic trough collector efficiency.

Odeh et al.[2]developed a mathematical model for steam production in a parabolic trough collector, focusing on absorber wall temperature. The model, applicable to any working fluid, considers internal convection, absorber emissivity, and phase shifts in liquid, boiling, and dry steam zones.

The exergetic performance of a concentrating type solar collector was assessed by Tyagi et al.[3], and the parametric research was conducted utilising hourly solar radiation. The exergy output was optimised in relation to the intake fluid temperature, and the efficiencies were calculated accordingly. Although most performance parameters, such as exergy output, exergetic and thermal efficiencies, stagnation temperature, inlet temperature, ambient temperature, and so on, increase as solar intensity increases, exergy output, exergetic and thermal efficiencies, and so on, are found to be an increasing function of mass flow rate for a given value of solar intensity. According to the authors, there is an ideal concentration ratio for a given mass flow rate at which the exergetic efficiency is best for a lower value of solar intensity.

Manikandan et al.[4]investigated the present PTC system using factors such as mass flow rate, concentration ratio, different heat transfer fluids (HTF), solar insolation, and heat removal factor. The results indicated that PTC efficiency falls with higher mass flow rates and HTF when the fluid inlet temperature rises.

The non-uniform heat transfer model and performance of a parabolic trough solar receiver were examined by Lu et al.[5], Energy balances among the heat transfer fluid, absorber tube, glass envelope, and surroundings were used to conduct a theoretical analysis. For unequal solar radiation and wall temperature distribution, the absorber tube and glass envelope were split into two zones. A non-uniform heat transfer model of the solar receiver was created.

Binotti et al.[6] offered an analytical technique to analyse the geometrical influence of three-dimensional (3-D) impacts on the optical performance of parabolic trough collectors as an extension of an established method – first-principle optical intercept computation (First OPTIC). As part of the First OPTIC code suite, the mathematical steps of this analytical method were provided and numerically implemented. Numerical solutions and ray-tracing simulation results were used to validate it. The 16 First OPTIC code is then used to a series of case studies to see how crucial 3-D factors affect the intercept factor.

The performance parameters of a Parabolic Trough Solar Collector system for hot water generation were studied by Valan Arasu and Sorna Kumar[7]. A one-square-meter aperture parabolic trough solar collector was conceived and built. It was claimed that the collector efficiency equation found in their study compares favourably to previous published research. The time constant for the collector derived from the test was 67 seconds. As measured by the test, the half acceptance angle of the collection was 0.5, which, when combined with the tracking system maximum error (0.18), indicates that the collector operates at maximum efficiency constantly.

Brooks et al.[8]carried out performance analysis and found that an evacuated glass shielded receiver and an unshielded receiver had peak thermal efficiencies of 53.8 percent and 55.2 percent, respectively.

Riffelmann et al. [9]devised two approaches for measuring solar flux in the focus region: The PARASCAN (Parabolic Trough Flux Scanner) device measures solar flux density and may be shifted along the receiver axis. With great resolution, the sensor measures the flux distribution in front and behind the receiver. The resultant flux maps enable calculation of the intercept factor and analysis of the collector's optical characteristics at the last important point, namely surrounding the receiver. The camera- target method (CTM) involves photographing a diffuse reflecting Lambertian target using a calibrated camera. Intercept losses might be identified and attributed to the points on the parabola where they occur. According to the researchers, the measured intercept factor was between 93 and 97.5 percent, although it drops below 85 percent for some receivers. This demonstrates the possibility to increase optical performance, not just by improving mirror-image quality but also by more precisely assembling collector components.

Lupfert et al.[10] used many approaches to assess solar parabolic trough collectors' geometry and optical characteristics, which have shown to be effective in prototype evaluation. Photogrammetry, flux mapping, ray tracing, and sophisticated thermal testing were used to create these. The findings of collector shape measurement, flux measurement, ray tracing, and thermal performance analysis for parabolic troughs are summarized in their paper. The findings of the measurement methods and parameter analysis were proven to be consistent. The results' interpretation and annual review provide insight into the identified relevant improvement potentials for the next generation of solar power plant collectors.

ValanArasu and SornaKumar[11]designed and manufactured a smooth 900 rim angle fiberglass-reinforced parabolic trough for solar collector hot water generating system by hand lay-up approach. The parabolic trough had a total thickness of 7 mm. The concave surface on which the reflector was mounted was finished to a high standard. The fiberglass-reinforced parabolic trough was put to the test under a load equal to the force provided by a 34 m/s wind. Wind loading caused some distortion of the parabola, but it was found to be within acceptable limits. ASHRAE Standard 93 was used to evaluate the thermal performance of the newly designed fiberglass reinforced parabolic collector. The collector performance test assessed the standard deviation of the distribution of parabolic surface errors to be 0.0066 rad.

Adeyemo and Adeoye [12]evaluated the performance of two separate solar heating systems, one of which tracked the sun while the other remained fixed. On clear and semi-cloudy days, they ran a 30-day performance test. The study found that over the same duration and under the same conditions, the tracking and non-tracking collectors had mean usable heat gains of 290 and 220 W/m^2, respectively, with total heat loss coefficients of 2.5 and 5.8 W/m2 k, and mean thermal efficiencies of 56 and 43 percent.

Lupfert et al. [13]reported field measurements and laboratory setups for evaluating receiver heat losses, both based on energy balances from the heated interior of the receiver tube to the ambient. More methods for measuring and analysing the temperature of the glass envelope of evacuated receivers and modelling the total heat losses and emissivity coefficients of the receiver have been provided. Very varied methods and autonomous installations have found a lot of common ground. Thermal loss has been found to be about 300 W per meter receiver length for solar parabolic trough systems operating in the normal 390°C temperature range.

By measuring flux, Schiricke et al. [14]experimentally confirmed optical modelling of parabolic trough collectors. The authors argued that studying the impact of collector and absorber geometry on optical performance is critical for optimizing the solar field output of parabolic trough collectors (PTCs). In commercial Monte Carlo ray-tracing software, the optical ray-tracing model developed by PTC for this purpose employs photogrammetrically determined concentrator geometry. The model was validated using data from a scanning flux measurement device that measured the solar flux density distribution near the PTC's focal line.

Chong et al.[15] suggested a cost-effective, easy-to-fabricate V-trough solar water heater system that uses a forced circulation method to increase solar water heater performance. The stationary V-trough solar water heater system's optical analysis, experimental investigation, and cost analysis were detailed. The testing findings reveal that the V-trough reflector's optical efficiency and the solar water heater's overall thermal performance were extremely promising.

Sagade et al.[16]tested a prototype parabolic trough composed of fiberglass-reinforced plastic and an aluminium foil reflector with a reflectivity of 0.86. This line-focusing parabolic trough was tested with and without a glass cover, and it features a mild steel receiver coated with black proxy material. With and without the glass cover, instantaneous efficiency was reported to be 51% and 39%, respectively.

The literature discussed above highlights that a significant number of researchers conducted experiments on CPCSWHs without incorporating twisted tape inserts in the absorber tube. The objective of the research article was to evaluate the collector's performance. Consequently, this study is designed to explore the impact of flow and geometric parameters on CPCSWH performance, considering both configurations with and without twisted tapes inside the absorber tube.

III. MATERIALS AND METHODS

The experimental setup for theCPCSWH was designed and constructed to investigate its efficiency in capturing and utilizing solar energy. The setup includes a water storage tank with a capacity of 30 L, a circulating pump, a Parabolic Concentrating Reflector (PCR), and an iron absorber tube. The PCR is made of acrylic mirror with a highly reflecting surface, with a total aperture area of 1.780m^2, which concentrates the incoming solar beam radiation to the absorber tube with a concentration. The specification about

The iron absorber tube is used as a solar radiation receiver, which is placed along the focus axis of the PCR. It is coated with black nickel coating, and is covered by a glass envelope to minimize heat losses through convection and conduction. The glass envelope is rectangular in shape with dimensions of length 121.92cm, breadth 7.62cm, and height 7.62cm, with good transmissivity. Rubber corks are incorporated at the ends of the glass envelope to achieve an air-tight enclosure.

The main function of the absorber tube is to absorb the concentrated solar radiation and transfer it to the water flowing through it. A pump is used to continuously circulate water through the absorber tube and into the water storage tank. A pump regulating knob is used to control the volumetric water flow rate (in L/min), which is measured by a water flow meter (Model: Jaldhara JWM 20mm Water Meter) fitted in line with the hydraulic hose pipe. Specification of each component of experimental setup is given below:

Table 1.
Experimental setup's component specification

S.No.	Components	Values
1.	Aperture area	1.780 m^2
2.	Internal surface area of absorber tube	0.082 m^2
3.	Length of absorber tube (L)	1.16 m
4.	Internal diameter of absorber tube	0.0254 m
5.	External diameter of absorber tube	0.026 m
6.	Width of the twisted tube	0.02 m
7.	Thickness of the twisted tube (t)	0.005 m

Hydraulic hose pipes are connected between the pump and water flow meter, absorber tube inlet, absorber tube outlet, and the water storage tank. The water storage tank is made of iron material and is rectangular in shape. It is insulated with glass wool and covered by a thick, black colour Rexene to prevent heat losses and is placed at the bottom of the cylindrical parabolic reflector.

Thermocouples are inserted on the surface of the absorber tube, inside the water storage tank, water storage tank inlet, as well as at the inlet and outlet of the absorber tube, to measure the water temperatures at the same locations. A display board, equipped with five digital temperature indicators connected with the thermocouples, is used to indicate the thermocouple's deflection (i.e., temperature readings).

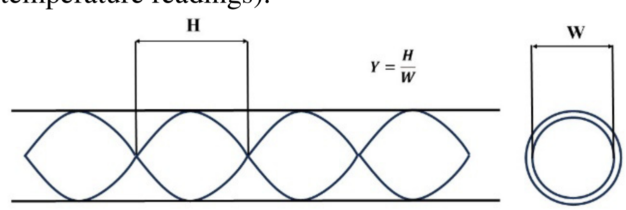

Fig. 1 Schematic view of twisted tape

To improve the heat transfer rate,twisted tape (Fig.1) with different twist ratio (Y) is used in the absorber tube. The pitch length (H)was varied to investigate the effect on the heat transfer rate.

The experimental setup will be exposed to solar radiation, and the volumetric flow rate, temperature, and solar radiation intensity will be measured and recorded. The data collected will be used to determine the efficiency of the CPCSWH in converting solar energy into heat energy and to optimize the design parameters of the absorber tube.

In the experimental setup (Fig. 2) of a solar water heater, meticulous steps are followed to evaluate its efficiency and performance.

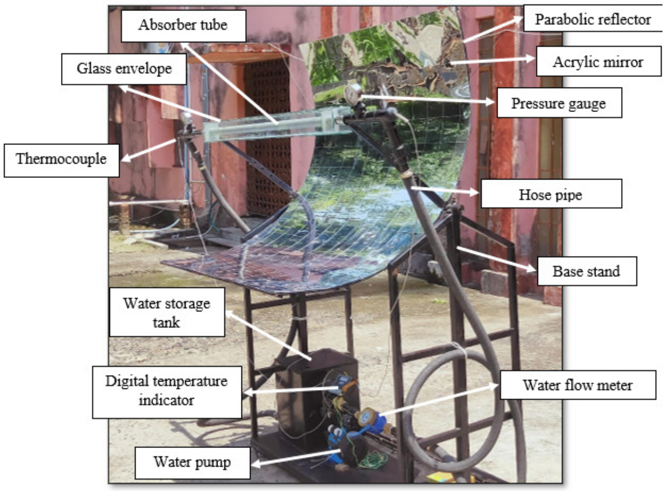

Fig. 2 Experimental setupCylindrical Parabolic Concentrating Solar Water Heater

First, the cylindrical parabolic reflector is precisely aligned to optimize solar radiation onto the absorber tube. Water fills the tank, circulated through the absorber tube via a pump while temperature sensors strategically placed measure the water and absorber tube temperatures. Concurrently, a data acquisition system begins recording various system parameters. Twisted tape inserts are then added to the absorber tube. The system is left to stabilize under sunlight, recording parameters at intervals to establish steady-state conditions. Utilizing recorded data, the solar water heater's efficiency is calculated. Further analysis of the experimental results examines the impact of twisted tape inserts on its performance.

IV. DATA REDUCTION

The mass flow rate of water is calculated as

$$m = \rho A V_w$$

In the copper absorber tube section, the velocity of water is obtained using the equation :

$$V_w = \frac{m}{\rho A_c}$$

where A_c is calculated as

$$A_c = \frac{\pi}{4} D_i^2$$

The twist ratios of the twisted tapes are calculated as

$$Y = \frac{H}{W}$$

The heat absorbed by the water is calculated as

$$Q = mC_p(T_o - T_i)$$

The instantaneous collector efficiency of the collector is presented as

$$\eta_i = \frac{mC_P(T_o - T_i)}{A_{ap} I_T}$$

The average Nu is estimated by using the equation

$$Nu = \frac{hD_i}{k}$$

The heat transfer coefficient has been calculated as

$$h = \frac{mC_p(T_o - T_i)}{A_i(T_r - T_b)}$$

The bulk mean temperature of the water is expressed as

$$T_b = \frac{T_i + T_o}{2}$$

The Re is given as

$$\mathrm{Re} = \frac{\rho V_w D_{h_t}}{\mu}.$$

The equivalent hydraulic diameter of the absorber tube without the twisted tape is calculated as

$$D_{h_p} = \frac{4A_c}{p} = \frac{4(\frac{\pi}{4} D_i^2)}{\pi D_i} = D_i.$$

The equivalent hydraulic diameter of the absorber tube with the twisted tape insert is calculated as

$$D_{h_t} = \frac{\pi D_i^2 - 4Wt}{\pi D_i + 2(W + t)}.$$

Friction factor, f, can be written as

$$f = \frac{\Delta p}{(\frac{L}{D_i})(\rho \frac{V_w^2}{2})}.$$

V. RESULTS AND DISCUSSION

A. *The effect of mass flow rate of water on the outlet temperature.*

The results displayed in Fig. 3, depict the impact of the mass flow rate of water, ṁ, on the outlet temperature of water (T_o)in a CPCSWH with and without twisted tapes inserted in the absorber tube.The findings indicate that the outlet temperature of water declines as the mass flow rate of water increases, regardless of the presence of twisted tapes in the absorber tube. Moreover, for a constant value of ṁ, the outlet water temperature, T_o, is higher in the presence of twisted tapes in the absorber tube compared to the scenario without any twisted tape inserts.

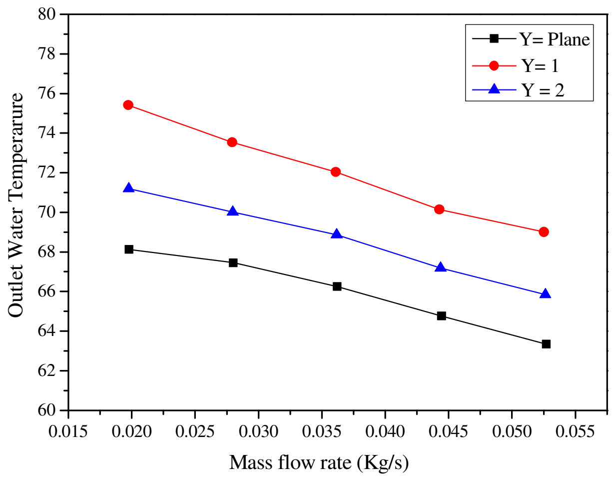

Fig. 3. Variation of the outlet temperature with the mass flow rate of water.

The cause for this is the development of swirl or turbulence flow of water inside the absorber tube, leading to an increased heat transfer from the absorber surface to the water flowing within the absorber tube. When ṁ is fixed at 0.01972 kg/s, T_o is found to be 75.50 °C at a lower twist ratio of Y = 1, while it is 71.30 °C at a higher twist ratio of Y = 2 and in case of plane twisted tape temperature reaches at only 68.00 °C.

B. *The effect of the mass flow rate of water on the instantaneous collector efficiency.*

Fig. 4, illustrates the relationship between the instantaneous collector efficiency, η_i, and the mass flow rate, ṁ, for different twist ratios. It can be observed that as ṁ increases, η_i also increases for both cases with and without twisted tape inserts in a CPCSWH. Moreover, the instantaneous collector efficiency is higher at lower twist ratios (Y) compared to higher twist ratios, across the entire range of water mass flow rates.

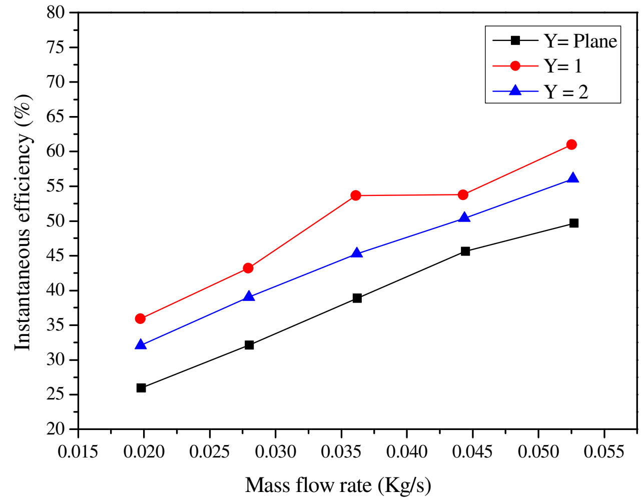

Fig. 4. Variation of the instantaneous efficiency, η_i, with the mass flow rate of water, ṁ, for different twist ratios Y.

When ṁ is fixed at 0.052516 kg/s, the instantaneous collector efficiency is 11.35% higher with a twist ratio of Y = 1 compared to no twist, and 4.92 % higher with a twist ratio of Y = 2. The increase in instantaneous collector efficiency with twisted tape inserts is attributed to the high heat transfer coefficient between the absorber surface and the flowing water within the absorber tube.

C. *The effect of the twist ratio on the Nusselt number.*

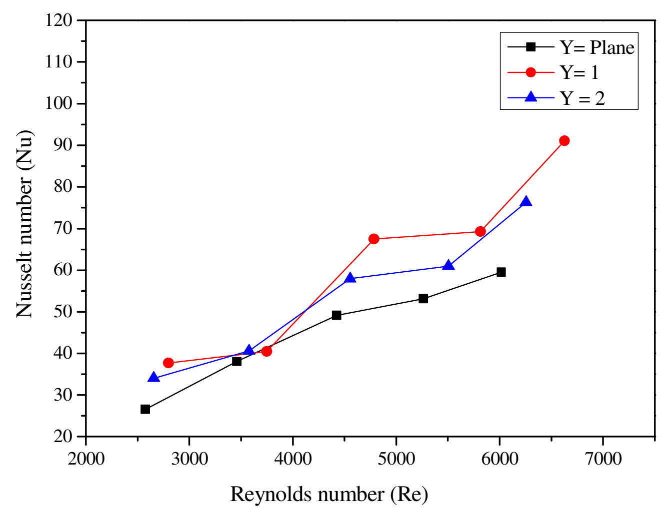

Fig. 5. Variation of Nu with Re for different twist ratios.

In Fig. 5, it can be observed that as Re increases, the Nu also increases for both the absorber tube with twisted tapes having ratios Y=0-2, and the absorber tube without any twisted tape inserts in the CPCSWH. However, the Nu values are consistently higher for the absorber tube with twisted tape inserts, compared to the one without them, across all Re values.

This can be attributed to the increased swirling action of water inside the absorber tube caused by the twisted tape inserts, resulting in a higher convection heat transfer coefficient between the absorber surfaces and the fluid.Additionally, it was found that for a fixed Re value, decreasing the twist ratio of the twisted tapes in the absorber tube leads to an increase in Nu. The increment Nu is found to be 41.77% higher in the lower twist ratio Y = 1 than with the no twist tape ratio Y = 0 for fixed Re.

D. *The effects of Reynold number and twist ratio on the pressure drop.*

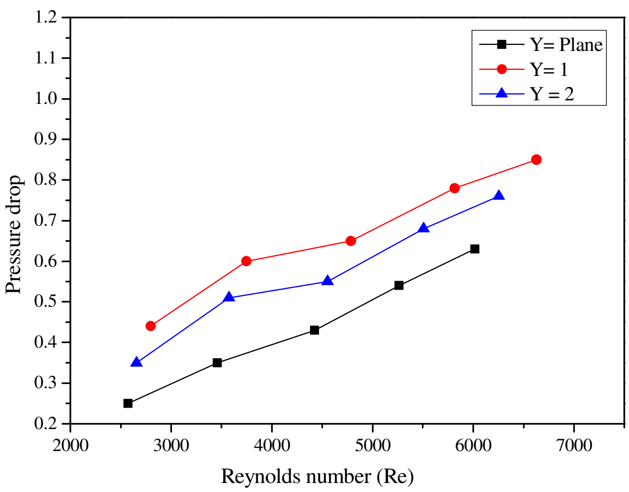

Fig. 6. Variation of Δp with Re for different twist ratios.

The results depicted in Fig. 6, illustrate the impact of Re and Y on the pressure drop (Δp) in the absorber tube, with and without twisted tape inserts of both ratios (Y=1&2). The data suggests that as Re increases, Δp also increases. Notably, the lowest twist ratio (Y=1) for the twisted tape exhibits the highest Δp across the entire range of Re in the CPCSWH. Consequently, the increased Δp of the fluids flowing through the absorber tube necessitates a greater pumping power to maintain the same outlet water temperature (T_o) and instantaneous collector efficiency.

E. *Variation of Friction Factor with Re and Twist Ratio*

In Fig. 7, the friction factor, f, for the absorber tube with twisted tapes of both ratios (Y = 1&2) and without twisted tape inserts is shown as a function of Re and Y. The curves for both cases, with and without twisted tape inserts, indicate that as flow Re increases, f decreases. For all Re ranges (2800-6627), f is highest at the lowest twist ratio (Y = 1) compared to the no twist and other twist ratios (Y = 2). These results are consistent with the higher values of T_o and Nu observed in the lower twist ratio (Y = 1) for the twisted tape inserts in the absorber tube of the CPCSWH.

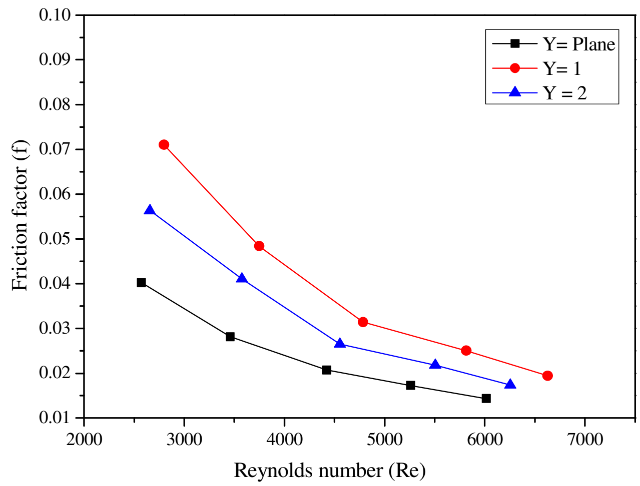

Fig. 7. Variation of 'f' with Re for different twist ratios

VI. CONCLUSION

The study investigated the effect of the mass flow rate of water and the twist ratio of the twisted tape inserts in the absorber tube on the outlet temperature, instantaneous collector efficiency, Nusselt number, pressure drop, and friction factor. The results showed that the outlet temperature of water decreased as the mass flow rate of water increased, regardless of the presence of twisted tapes in the absorber tube. However, for a constant value of mass flow rate, the outlet water temperature was higher in the presence of twisted tapes in the absorber tube than without them. This was due to the development of swirl or turbulence flow of water inside the absorber tube, leading to increased heat transfer from the absorber surface to the water flowing within the absorber tube.

Moreover, the instantaneous collector efficiency increased as the mass flow rate of water increased, and it was higher at lower twist ratios of the twisted tape compared to higher twist ratios. The increase in instantaneous collector efficiency with twisted tape inserts was attributed to the high heat transfer coefficient between the absorber surface and the flowing water within the absorber tube. The Nusselt number was consistently higher for the absorber tube with twisted tape inserts than without them, across all Reynolds number (Re) values. Additionally, decreasing the twist ratio of the twisted tapes in the CPCSWH led to an increase in Nusselt number.

The pressure drops in the absorber tube increased as the Reynolds number increased, and the lowest twist ratio of the twisted tape exhibited the highest pressure drop across the entire range of Reynolds number in the CPCSWH. The friction factor decreased as the Reynolds number increased, for both cases, with and without twisted tape inserts.

In summary, the study showed that the use of twisted tape inserts in the absorber tube of a CPCSWH could improve the heat transfer rate, thereby increasing the instantaneous collector efficiency. However, the use of twisted tape inserts also increased the pressure drop, which necessitated greater pumping power to maintain the same outlet water temperature and instantaneous collector efficiency. The results of the study provided insights into the optimization of the design parameters of a CPCSWH for efficient utilization of solar energy.

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