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Experimental Study to Evaluate the Thermal Performance of a Parabolic Trough Solar Collector Using a Twisted Absorber Tube

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ABSTRACT

This study focuses on improving parabolic trough solar collector performance by enhancing thermal energy storage, increasing heat transfer, and optimizing efficiency. It also investigates the influence of twisted tubes and environmental factors (wind, pollution) through experimental analysis under three different mass flow rates. Having a width of 0.9 m, a length of 1.8 m, and an area of 1.62 m^2, the PTSC, symbolizing parabolic trough solar collector, is constructed and produced. Sheets of stainless steel are used to coat the parabolic trough. The heat is absorbed by a copper twist tube. Both its outside and inside diameters are 0.0125 meters and 0.0105 meters, respectively. Where the volume flow rate of water employed as a heat transfer medium was 2, 4, 6 L/min. The tests were conducted utilizing outdoor measurements to assess the pressure drop, instantaneous thermal efficiency, and useful heat gain. The effects of ambient conditions, the working fluid's mass flow rate variation, and the collector inlet temperature were examined in the PTC array's performance analysis. For solar collectors with non-evacuated glass receivers, peak efficiencies of roughly 23%, 20%, and 15% were achieved. The collector efficiency equation derived from this study shows good agreement with the other published works. The final outcomes found that the technique of utilizing PTC shows that, as the quantity of solar radiation rises, thermal efficiency, the variation between the temperatures at the input and the output, and the useful heat improvement all rise, and the twisted tube raises the performance of the solar collector from the normal tube.

1. INTRODUCTION

One type of concentrating solar power technology is called a parabolic trough collector, which directs sunlight onto receiver tubes using parabolic-shaped reflectors, demonstrating their adaptability and efficiency potential by producing high temperatures for uses such as desalination, refrigeration [1]. This method makes use of a twisted tube, which improves internal fluid mixing and lowers thermal losses to increase heat transfer efficiency. Better thermal performance and greater energy absorption are the results of this design.

The solar system's performance is upgraded by evacuated receivers, which result in a 70% increase in thermal efficiency, and inserts and nanofluids, which increase heat transmission by up to 340% [2].

When compared to straight tubes, twisted tapes in U-tubes enhanced heat transfer by up to 85% and pressure drop by up to 3.2 times; the effects were stronger at higher Reynolds numbers (4,250–12,750) [3].

In the study of Hari et al. [4], the maximum efficiency was demonstrated by Ni-Al and Ni-Cr coated copper tubes with seawater, demonstrating the value of sophisticated coatings and heat transfer fluids in improving collector performance.

In the research of Tang et al. [5], experimental research proved that the twisted trilobed tube created an 8.4% increase in friction while at the same time allowing for an enhancement in heat transfer by 5.4%. However, it displayed better thermal efficiency, thus proving to be a better option for heat transmission applications.

The 128 mm diameter twisted elliptical tube performs best overall, increasing heat transfer by up to 19% while increasing pressure drop by up to 60% [6].

In the study of Aldulaimi [7], the effectiveness of the TTT absorber tube was 59.8%, whereas that of a plain tube was 41.9%. Theoretical models were confirmed by the fact that increasing flow rates increased pressure drop while decreasing temperature difference.

The parabolic trough collector demonstrated its sustainability as a renewable energy source by producing inexpensive power and cleaned water with efficiency [8].

The necessity of appropriate transient load control was emphasized by the upgraded M2 approach, which showed notable thermal and structural changes in evacuated receivers at cold starts and low flow rates [9].

Lotake and Wagh [10] increase mass flow boosted efficiency by 1.37 times (black-painted) and 1.3 times (unpainted); manual tracking provided 1.04–1.1 times improvement, and black paint increased efficiency by 1.16 times.

Rotating the absorber tube provided a practical, affordable improvement by reducing the temperature differential by 60%, lowering the surface temperature by 15%, and increasing efficiency by 17% [11].

Temperature variations up to 199.7 K were generated by a 1.63% receiver misalignment, which also reduced optical efficiency by 32% and total efficiency by 14% [12].

In order to improve heat transfer, Zheng et al. [13] examine a multihead twisted spiral tube (MTST). Results show that efficiency increases with a larger diameter ratio, more spiral heads, and more twisted nodes.

Internal barriers in twisted tubes increase efficiency and heat transfer while increasing flow resistance; the best design strikes a compromise between the two for the best thermal performance [14].

Parabolic trough collectors (PTCs) were used to study the effect of a rotating receiver tube on heat transmission [15]. The water temperature increased by 18.5℃ and friction increased up to 137.5 times at 4 rpm, according to the results, improving thermal performance. But with rotation, the friction factor rose noticeably.

By integrating structural and optical studies, Rao and Reddy [16] suggested a method for optimizing PTC design. It took wind effects into account while optimizing collector width, rim angle, slope errors, and tracking errors. This method increased the efficiency of solar energy gathering.

In the study of Elbassiti et al. [17], with minimal pressure drop, triangular internal fins in parabolic trough collectors boost turbulence and enhance heat transfer efficiency by 4.5% to 13.4%.

Jurmut et al. [18], helical tape in evacuated tubes enhanced the temperature of the water in storage tanks by 19% and boosted collector efficiency from 28% to 36%. In parabolic trough collectors with an 11.7 concentration ratio and an 85% reflecting segmented mirror, black-coated tubes demonstrated the highest efficiency.

The impact of mass flow rate and tilt angle on a parabolic trough collector's thermal performance is investigated in this work. with the goal of promoting sustainable energy consumption and improving performance [19].

When compared to smooth tubes, heat transport in CCD tubes was enhanced by almost five times [20]. In addition to decreased heat loss and an excellent balance between pressure drop and performance efficiency, the outlet fluid temperature rose by 11.4%.

According to the study of Razzaq and Mushatet [21], numerical analysis of a double twisted tube heat exchanger, a lower twist ratio (Tr = 5) increased total performance by 13% and heat transmission by 14%. A compromise between heat transfer efficiency and flow resistance was necessary because the twisted design increased pressure drop while also increasing thermal turbulence

Naveenkumar and Soudagar [22] used a solar-powered motor to rotate the PTC receiver tube increasing heat dispersion, decreasing thermal stress, increasing water temperature from 28 to 51 degrees Celsius, increasing efficiency by 38%, and cutting the payback period by 20 days.

Munusamy and Shreedhar [23] enhance parabolic trough solar water heaters by employing twisted copper dimple tubes with an aluminum covering, leading to an efficiency gain of 31.25% at a 1.5 kg/min flow rate.

Through the use of hybrid nanofluids and an elliptical tube, Touaref and Farkas [24] increase the solar collectors' efficiency by 45.46% and improve heat transfer by 25%. It has a straightforward, efficient design and works well for desalinating water. Additional testing and AI tuning will be part of future efforts.

According to the study of Geng and Gu [25], improved fluid flow and heat transmission are achieved by incorporating a helical rotor into the PTC's heat collecting tube, resulting in a roughly 30% increase in heat collection and efficiency over conventional tubes.

2. EXPERIMENTAL SET-UP

2.1 Experimental rig

This study conducted an experiment on the parabolic trough solar collector's thermal efficiency utilizing a twisted copper tube and measuring devices as the main part of the experimental setup as illustrated in Figure 1.

(a) Wind speed meter

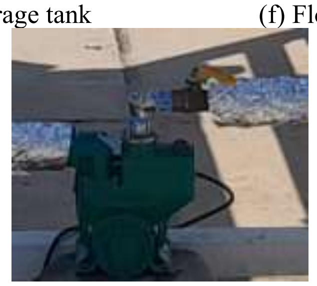
(b) Solar power meter

(c) Digital pressure manometer

(d) Temperature recording

(e) Storage tank

(f) Flow meter



(g) Water pump

Figure 1. Experimental work of parabolic trough solar collector

The roof of the Al Mussaib College Technical Faculty served as the location for the system's installation and testing in January and February 2025. The approximate latitude and longitude of Iraq are 32.48389° and 44.43111°, respectively. The tilt angle of this solar collector is designed to be suitable for the nearby latitude. The tilt of the PTSC is set to 45° towards the south. Practical tests were conducted in a cold environment from 9 AM to 2 PM. It was the PTC, symbolizing Parabolic Trough Collector, consisting of a reflector made of chrome-coated steel sheets, shaped according to the equation with a meter and an aperture width of 1.4 meters. The reflector is fixed using side ribs made of fiber or wood and steel angles, with a circular hole to secure the glass receiver tube. The PTC is mounted on a steel support structure and connected to a 2-inch diameter steel tube that houses the copper absorber pipe. The structure is equipped with wheels for easy positioning and adjustment. As presented in Figure 2.

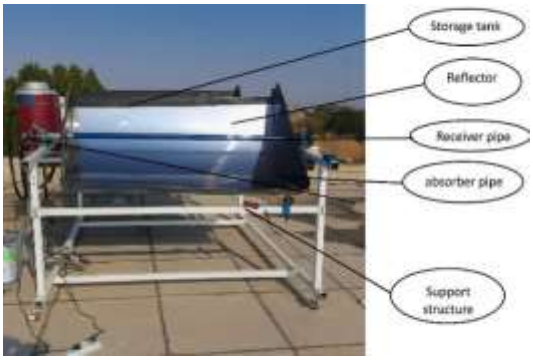


Figure 2. Displays the experimental setup

Thermal receiver consists of a glass tube, bushings, a ring, and a support plate. The two coaxial borosilicate glass tubes compose the glass tube, as illustrated in Figure 3. One end is open for outlet and inlet, while the other end is sealed. The glass tube has the following dimensions: inner diameter 47 mm, outer diameter 58 mm, length 1800 mm for the cover tube, and length 3600 mm for the absorbing double-twisted copper tube. The glass thickness is 1.6 mm. In order to enhance the absorption, an aluminum nitrite selective coating covers the inner tubes exterior. The parabolic trough's focal line is where the receiver has been positioned. Glass tube specifications are given in Table 1.

Figure 3. Non evacuated glass tube

Table 1. Glass tube specifications

ITEM	Value
Cover diameter	58 mm
Receiver length	1800 mm
Emissivity	0.08
Coated surface absorptance	0.93
Cover transmittance	0.91

To absorb heat, the collectors' absorber pipes are made of enclosed, double-twisted copper pipes that are coated with black paint and have an outer diameter of 1/2″. One end of the enclosed pipes has been welded to the other, leaving the other ends unattached. The enclosed pipes, as illustrated in Figure 4, are utilized for simultaneous fluid entry and exit. Conversely, the 44 mm inner diameter of the glass receiver tube was used to house the absorber pipes. To seal the glass tube's opening, a fiberglass bung is placed at the glazing receiver's opening and encircles two copper pipes firmly, thereby preventing the flow of convection between the vacuum tubes with double glazing and the annular one. To support the copper pipes inside and prevent them from coming.

In contact with the glass structure, Teflon is used at the glass tube's near and far ends.

Figure 4. Twisted copper pipe

3. EXPERIMENTAL PROCEDURE

(1) Recording Intervals: Every half an hour, parameters were recorded.

(2) It's critical to remove any collected dust or dirt from the reflectors (mirrors).

(3) After that, the water from the main line is used for filling the storage tank. The water recirculation network's storage tank holds 40 liters of water because it is open. By connecting the storage tank's inlet to the trough outlet and its outlet to the troughs' inlet, the two can be connected to the troughs system. After the pump is set up, the flow meter is put in place to monitor the water's rate of flow through the pipes. Water returns to the storage tank once it has heated up and accumulated heat.

(4) Temperature is measured at the absorber tube, inlet, and outflow.

(5) Along the PTSC, thermocouples are positioned at different points.

(6) A solar power meter examines the energy that the sun emits.

(7) Thermocouple measurements are recorded by the temperature thermometer.

4. RESULTS AND DISCUSSION

Twisted copper pipes coated in black are used in parabolic trough solar collectors to improve heat conversion efficiency and solar energy absorption, as the twisted shape generates a vortical flow even at low speeds, enhancing the effectiveness of heat transfer compared to straight pipes.

Environmental factors including ambient air temperature and sunlight intensity significantly affect the efficiency of parabolic trough solar collectors. Experimental tests began at

9:00 AM and lasted until 2:00 PM. The ambient temperature ranged from 9.3°C to about 23°C by 2:00 PM.

Solar radiation intensity greatly influences the amount of energy harnessed by the solar collector. The solar irradiance was approximately 418 W/m² at 8:30 AM, increased to 986 W/m² at 12:00 PM, and then decreased to 763 W/m² at 2:00 PM. The experimental sessions extended until 2:00 PM.

As solar radiation rose, so did the fluctuation in outlet temperature profiles. Additionally, it peaked during the height of solar radiation. At a 6 L/min flow rate, the PTSC's highest exit temperature was 54.6°C. The trend seen in the changes in the rate of mass flow was also seen in the output temperature profiles. Showing that the outlet temperature rose as solar radiation increased, peaking when solar energy intensity was at its maximum. Furthermore, the temperature profiles decreased in the afternoon as a result of less sunlight.

The proportion of the collector's heat to the entire quantity of incident solar energy is known as the PTSC's thermal efficiency. The following formula can be applied to find the thermal efficiency:

$$\eta = \frac{Qu}{Ac\ I}$$

where, Ac is the collector's aperture area (in square meters), Qu is useful heat gain, and I is solar radiation.

The instantaneous heat energy that the HTF acquires while passing through the PTC's intake and exit is known as the useful heat gain.

$$Qu = \text{m}^{\circ} C_p (T_{out} - T_{in})$$

where, C_p denotes the specific heat of the water $(\frac{kJ}{kg}.C^{\circ})$, m° denotes te mass flow rate $(\frac{kg}{s})$, T_{in} denotes the inlet water temperature (°C) and T_{out} denotes the outlet water temperature (°C).

Across the twisted tube length (L), the pressure drop (Δp) was tracked with a digital pressure gauge installed throughout the test area. As a function of the friction factor (f), the pressure loss can be written as:

$$f = \frac{\Delta p}{\frac{1}{\rho u^2}} \cdot \frac{Di}{L}$$

where, f denotes the Darcy friction factor (dimensionless), L denotes the pipe length (m), Δp denotes the pressure drop (Pa), ρ denotes the fluid density (kg/m³), u is the average fluid velocity (m/s), Di denotes the pipe's inner diameter (m).

In Figure 5, there is a noticeable downward tendency in the graph that depicts the temperature differential (ΔT) throughout a twisted tube at various flow speeds (2, 4, and 6 L/min). In addition, the variation in temperature between the collector's inlet and outlet has an inverse relationship with the flow rate of HTF inside the collectors. The temperature differential inside the collector decreases as the flow rate rises. This behavior reflects that, whenever the fluid flows inside the collector more slowly, it can collect greater heat from the solar radiation. So, it is observed from the Figure 5 that as the fluid flow rate is at its lowest value, the outlet temperature has the highest value.

In Figure 6, because of the strong turbulent flow and improved mixing brought on by the tube's twisting, which greatly enhances convective heat transfer, the maximum usable heat gain happens at 6 L/min. With slightly less residence time than at 2 L/min, the usable heat gain is reasonably high at 4 L/min, benefiting from more turbulence in comparison to lower flow. Despite a longer residence period, the beneficial heat gain is lowest at 2 L/min because the flow is slower and more laminar, which lowers the overall heat transfer rate.

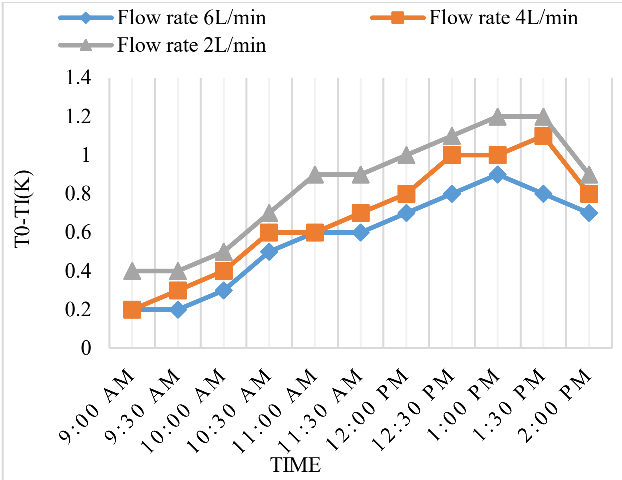


Figure 5. Water temperature differences through collectors in relation to local time

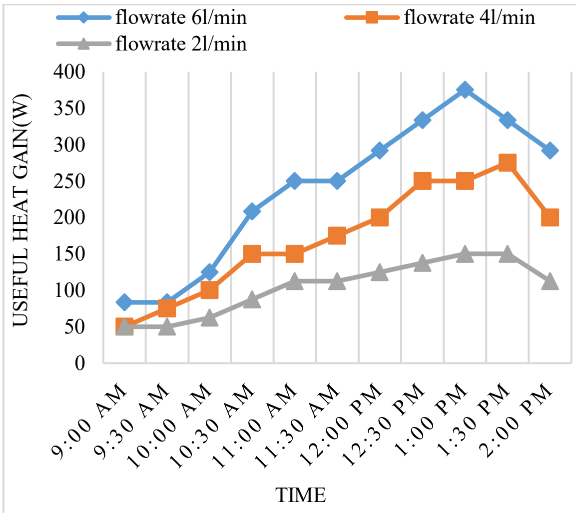


Figure 6. Comparison between flow rate heat gain for non evacuated receiver pipe

In Figure 7, the instantaneous thermal efficiency of the collector has a direct proportionality to the HTF flow rate through the collector. The thermal efficiency rises as the flow rate does. For instance, when the values of flow rates were 2 LPM, LPM, and LPM, the instantaneous thermal efficiency increased by 15%, 20%, 23%. It happens because the collector's maximum heat gain occurs when the flow rate is at its maximum, which lowers heat losses and increases heat gain and thermal efficiency. Because thermal efficiency depends on both solar radiation and heat gain, it has been found that patterns of variation in thermal efficiency throughout the day are similar to those of heat gained [5].

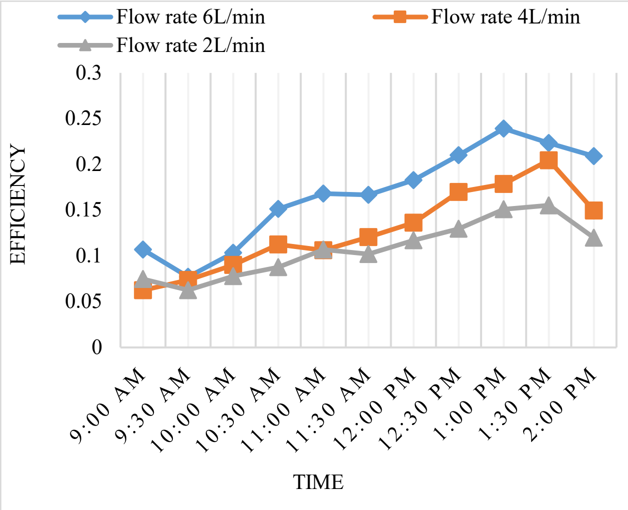


Figure 7. Thermal efficiency comparison for various days at various flow rates

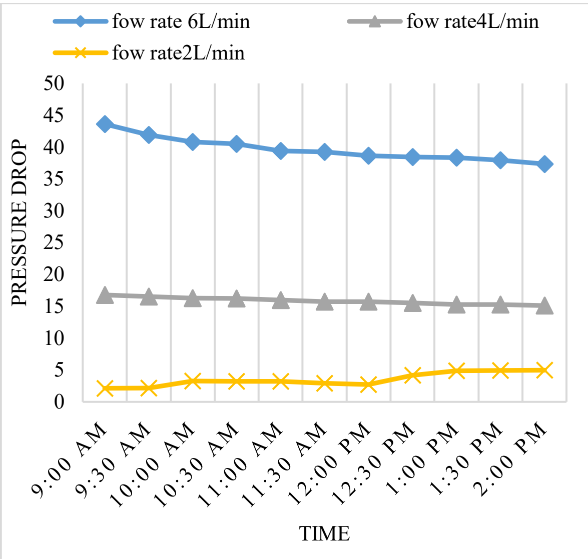


Figure 8. Comparison between pressure drop for various days at various flow rates

The pressure drops inside a twisted pipe at various flow rates (2, 4, and 6 L/min) are represented by this curve in Figure 8. We can observe that the highest pressure drop occurs at 6 L/min because of the high speed and increased turbulence brought on by the tube's shape, which greatly resists flow. A rate of 4 L/min follows, with a marginally smaller pressure drop but still a high one because of the vortices' ongoing influence. Because of the comparatively low velocity, the pressure drop is then lessened, reaching its lowest value at 2 L/min, where the flow is weaker and the friction is lower. The curve, which shows the direct correlation between flow rate and pressure loss in twisted pipes, rises from 2 to 6 L/min.

Figure 9 illustrates that because 6 L/min produces the most turbulence and vortices inside the twisted tube and, consequently, the largest internal resistance, this rate exhibits the highest coefficient of friction in this curve. The coefficient of friction then somewhat drops at 4 L/min. Lastly, the coefficient of friction is lowest in this curve at 2 L/min because the flow is semi-stratified and the liquid velocity is low, which lowers overall friction even when heat transfer is poor.

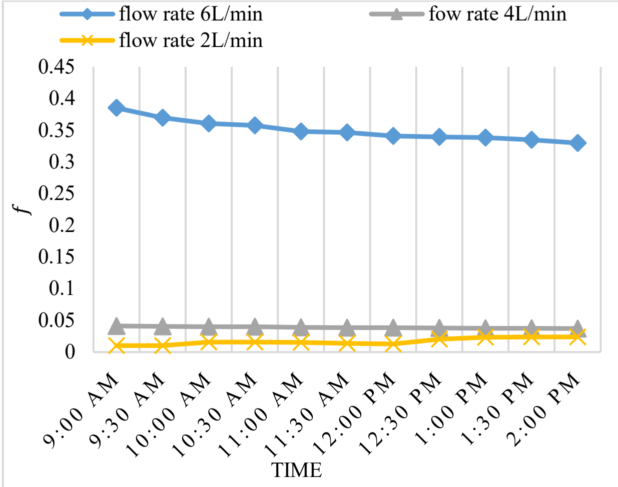


Figure 9. Comparison between fraction factor for various days at various flow rates

5. CONCLUSIONS

In this study, a parabolic trough solar collector was examined experimentally utilizing a twisted tube absorber with different volumetric flow rates: 2 L/min,4 L/min, 6 L/min. The collected data and verified results lead to the following conclusions:

(1) As the feed water flow rate decreases, the temperature differential across the collectors widens.

(2) As the rate of feed water flow and the intensity of solar radiation increase, so does the useful heat gain.

(3) As solar radiation intensity and feed water flow rate increase, so does the instantaneous thermal efficiency.

(4) As the flow rate increases, so does the pressure drop across the pipes' fluid entry-exit zone.

(5) The study showed that the friction factor was highest at 6L/min, followed by 4 L/min, 2 L/min.

(6) The study showed that the twisted tube raises the efficiency of the solar collector from the normal tube.

6. RECOMMENDATION

(1) It is possible to test various absorber coating materials to determine how they affect the system's performance.

(2) The system can also be used to test PTCs with the widest aperture widths to observe how they affect performance.

(3) Several types of working fluids can be used to see their effects on the thermal efficiency. Various types of nanofluids with different concentrations can be used.

REFERENCES

[1] Fernández-García, A., Zarza, E., Valenzuela, L., Pérez, M. (2010). Parabolic-trough solar collectors and their applications. Renewable and Sustainable Energy Reviews, 14(7): 1695-1721. https://doi.org/10.1016/j.rser.2010.03.012

[2] Sandeep, H., Arunachala, U. (2017). Solar parabolic trough collectors: A review on heat transfer

augmentation techniques. Renewable and Sustainable Energy Reviews, 69: 1218-1231. https://doi.org/10.1016/j.rser.2016.11.242
[3] Farnam, M., Khoshvaght-Aliabadi, M., Asadollahzadeh, M. (2018). Heat transfer intensification of agitated U-tube heat exchanger using twisted-tube and twisted-tape as passive techniques. Chemical Engineering and Processing-Process Intensification, 133: 137-147. https://doi.org/10.1016/j.cep.2018.10.002
[4] Hari Haran, V., Venkataramaiah, P. (2020). Study on solar parabolic trough collector with different copper absorber tubes. Intelligent Manufacturing and Energy Sustainability, pp. 271-278. https://doi.org/10.1007/978-981-15-1616-0_26
[5] Tang, X., Dai, X., Zhu, D. (2015). Experimental and numerical investigation of convective heat transfer and fluid flow in twisted spiral tube. International Journal of Heat and Mass Transfer, 90: 523-541. https://doi.org/10.1016/j.ijheatmasstransfer.2015.06.068
[6] Wu, C.C., Yang, Y.T., Huang, K.H. (2018). Numerical simulation of turbulent flow forced convection in a twisted elliptical tube. International Journal of Thermal Sciences, 132: 199-208. https://doi.org/10.1016/j.ijthermalsci.2018.05.028
[7] Aldulaimi, R.A.K.M. (2019). An innovative receiver design for a parabolic trough solar collector using overlapped and reverse flow: An experimental study. Arabian Journal for Science and Engineering, 44: 7529-7539. https://doi.org/10.1007/s13369-019-03832-8
[8] Tahjib, A., Tanzin, H., Azim, H., Rahman, S.I. (2020). Design and implementation of parabolic trough solar thermal collector. In 2020 IEEE Region 10 Symposium, Dhaka, Bangladesh, pp. 670-673. https://doi.org/10.1109/TENSYMP50017.2020.9230854
[9] Lotake, S.N., Wagh, M.M. (2020). Performance evaluation of multiple helical tubes as a receiver for solar parabolic trough collector. Asia Pacific Journal of Energy and Environment, 7(1): 39-46.
[10] Li, L., Yu, H., Li, Y., He, Y.L. (2020). Characteristics of the transient thermal load and deformation of the evacuated receiver in solar parabolic trough collector. Science China Technological Sciences, 63: 1188-1201. https://doi.org/10.1007/s11431-019-1508-y
[11] Norouzi, A.M., Siavashi, M., Ahmadi, R., Tahmasbi, M. (2021). Experimental study of a parabolic trough solar collector with rotating absorber tube. Renewable Energy, 168: 734-749. https://doi.org/10.1016/j.renene.2020.12.088
[12] Donga, R., Kumar, S., Kumar, A. (2021). Performance evaluation of parabolic trough collector with receiver position error. Journal of Thermal Engineering, 7(1): 271-290. https://doi.org/10.18186/thermal.849869
[13] Zheng, Z., Yan, F., Shi, L. (2022). Numerical study on heat transfer and flow resistance characteristics of multi-head twisted spiral tube. Thermal Science, 26(2): 1883-1895. https://doi.org/10.2298/TSCI210224206Z
[14] Alsulaiei, Z.M., Hasan, H.M., Fagr, M.H. (2021). Flow and heat transfer in obstacled twisted tubes. Case Studies in Thermal Engineering, 27: 101286. https://doi.org/10.1016/j.csite.2021.101286
[15] Reddy, N.S., Subramanya, S.G., Vishwanath, K., Karthikeyan, M., Kanchiraya, S. (2022). Enhancing the thermal efficiency of parabolic trough collector using rotary receiver tube. Sustainable Energy Technologies and Assessments, 51: 101941. https://doi.org/10.1016/j.seta.2021.101941
[16] Rao, B., Reddy, K. (2022). Optical and structural optimization of a large aperture solar parabolic trough collector. Sustainable Energy Technologies and Assessments, 53: 102418. https://doi.org/10.1016/j.seta.2022.102418
[17] Elbassiti, H., Adwan, M., Darhmaoui, H., Sheikh, N. (2023). Numerical investigation of heat transfer enhancement in a parabolic trough receiver using triangular fins. AIP Conference Proceedings, 2761(1): 040014. https://doi.org/10.1063/5.0172350.
[18] Jurmut, H.A., Nasir, K.F., Al-Hamadani, H. (2023). Effect of using helical tape inside tubes on the performance of evacuated tubes solar collector. AIP Conference Proceedings, 2776(1): 060005. https://doi.org/10.1063/5.0137304
[19] Itabiyi, O., Sangotayo, E., Olojede, M., Akinrinade, N., Oluwafemi, O., Bhadmus, G. (2024). The effect of tilt angle and mass flow rate on the performance of a parabolic trough solar concentrator via experimentation. Advances in Physics Theories and Applications, 88: 1-10. https://doi.org/10.7176/APTA/88-01
[20] Khalil, M., Rieck, J., Wellmann, J., Behrendt, F. (2024). Corrugated circular dimple absorber for heat transfer augmentation on parabolic trough solar receiver. International Communications in Heat and Mass Transfer, 159: 108041. https://doi.org/10.1016/j.icheatmasstransfer.2024.108041
[21] Razzaq, A.K.A., Mushatet, K.S. (2021). A numerical study for a double twisted tube heat exchanger. International Journal of Heat and Technology, 39(5): 1583-1589. https://doi.org/10.18280/ijht.390521
[22] Naveenkumar, R., Singh, P.K., Ravichandran, M., Mohanavel, V., Venkateshkumar, R., Kedia, A., Kannan, S., Soudagar, M.E.M. (2025). Thermal performance analysis of a parabolic trough collector based solar water heater using revolving absorber tube. Results in Engineering, 25: 104270. https://doi.org/10.1016/j.rineng.2025.104270
[23] Munusamy, A., Barik, D., Chandran, S.S., Reby Roy, K., Paramasivam, P., Shreedhara Murthy, S. (2024). Experimental analysis of the effect of copper dimple tube with aluminum coating on the performance of parabolic solar water heater using helically twisted tape. Advances in Mechanical Engineering, 16(7): 1-12. https://doi.org/10.1177/16878132241262679
[24] Touaref, F., Seres, I., Farkas, I. (2025). Optimisation of heat transfer in the absorber tube of a cylindroparabolic trough solar collector. Results in Engineering, 26: 105226. https://doi.org/10.1016/j.rineng.2025.105226
[25] Geng, Z., Chen, K., Li, Y., Jiang, Y., Hua, K., Liu, S., Gu, Y. (2025). Coupled flow-thermal performance analysis of parabolic trough collector enhanced by helical rotor inserts in vacuum collector tube. Applied Thermal Engineering, 274(15): 126711. https://doi.org/10.1016/j.applthermaleng.2025.126711