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Augmenting the Performance of Evacuated Tube Solar Water Heater Using Perforated Wavy Tape

Punam Kumar Agade[1], Nitin Dubey[2], Rahul Agrawal[3].

[1,2]Department of Mechanical Engineering, Madhyanchal Professional University, Bhopal, 462044, Madhya Pradesh, India.
[3]Department of Mechanical Engineering, Prestige Institute of Management and Research, Bhopal, 462022, India.

E-*mail:* [1] agade.punam288@gmail.com , [2] nitindubey123@gmail.com , [3] rahul.210489@gmail.com .

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ABSTRACT

A significant portion of energy is wasted within the evacuated tube collector due to the formation of an inactive zone at the bottom of the tube, resulting in decreased efficiency. The current study presents an experimental investigation of the energetic and exergetic analysis of an evacuated tube solar water heater associated with perforated wavy tubes. A comparative analysis of conventional solar water heater and water heater with three different thermal enhancement methods was carried out: The use of wavy tape inserts (Plain WT), perforated wavy tape with 6 mm equilateral triangles (6 PWT), and perforated wavy tape with 9 mm equilateral triangles (9 PWT).

The results showed that the insertion of wavy tapes improved the temperature of the ETC solar water heater's tank water as well as the temperature of the evacuated tubes. The highest hourly efficiency was recorded as 83.33% for the ETSC with 6 PWT, followed by 81.8%, 78.3%, and 75.6% for the ETSC with 9 PWT, ETSC with plain WT, and ETSC without WT, respectively. The effect of perforated wavy tape ETSC (6 PWT) resulted in a daily energy efficiency of 49.3%, which is greater than without WT (38.7%), with plain WT (44.9%), and with 9 PWT (47.8%). The average exergy efficiency of ETSC with 6 PWT was higher by 70.1%, 35.1%, and 13.1% compared to without WT, with plain WT, and with 9 PWT, respectively.

*Corresponding author.

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تحسين أداء سخانات مياه الطاقة الشمسية ذات الأنبوب المفرغ باستخدام شريط مموج مُثقَّب

بونام كومار أغادي، نيتين دوبي، راهول أغراوال.

ملخص: يُهدر جزءٌ كبيرٌ من الطاقة في مجمعات الأنبوب المفرغ بسبب تكوين منطقة غير نشطة في الجزء السفلي من الأنبوب، مما يؤدي إلى انخفاض الكفاءة. تقدم الدراسة الحالية تحليلا تجريبيا لسخان المياه الشمسي ذو الأنبوب المفرغ المرتبط بالأنابيب المتموجة المثقبة. كذلك أُجريت مقارنة لأداء سخان مياه شمسي تقليدي وسخان المياه مع ثلاث طرق مختلفة لتعزيز الاداء الحراري: وذلك باستخدام شريط مموج (Plain WT)، وباستخدام شريط مموج بثقوب على شكل مثلثات متساوية الأضلاع مقاس 6 مم (PWT 6)، وباستخدام شريط مموج بثقوب على شكل مثلثات متساوية الأضلاع مقاس 9 مم (PWT 9). أظهرت النتائج أن إستخدام الأشرطة المتموجة أدى إلى ارتفاع في درجة حرارة ماء سخان المياه الشمسي، وكذلك درجة حرارة الأنابيب المفرغة. وسج لت أعلى كفاءة حوالي 83.33% للمجمع الشمسي بالشريط المموج ذو الثقوب (PWT 6)، و 81.8% للمجمع الشمسي بالشريط المموج من نوع (PWT 9)، 78.3% للمجمع الشمسي بالشريط المموج الغير مثقب (Plain WT)، و 75.6% للمجمع الشمسي التقليدي. كما تم قياس متوسط الكفاءة اليومية للمجمعات المدروسة وكانت، للمجمع الشمسي (PWT6) حوالي 49.3%، وللمجمع الشمسي التقليدي حوالي 38.7%، وبلغت كفاءة المحمع الشمسي (Plain WT) حوالي 44.9%، و للمجمع الشمسي (PWT9)حوالي 47.8%. وهو ما يمثل زيادة في الكفاءة عن المجمع الشمسي المسطح التقليدي بحوالي 70.1%و 35.1% و 13.1% للمجمعات الشمسية من نوع (PWT6) ومن نوع (Plain WT) ومن نوع (PWT 9)، على التوالي.

الكلمات المفتاحية – مجمعات الأنابيب المفرغة، الشريط المتموج، الطاقة، الكفاءة، الاكسيرجي، التثقيب، درجة حرارة الماء.

1. INTRODUCTION

The quest for energy is continually increasing each day due to growing consumption across domestic and industrial sectors [1,2]. Due to global economic and technological advancements, energy consumption has recently increased by 44.2% overall for the 2006–2030 projected period [1]. Energy is essential for various purposes such as heating, transportation, and lightening in our daily lives. Research by Reddy et al. [3] reveals that approximately half of the global energy demand is attributed to heat production for many purposes [4]. The continued utilization of traditional resources like fossil fuels to fulfill excess energy needs results in their eventual depletion. Rooftop solar systems are now the market's most distinctive, cutting-edge, and lucrative options. A detailed life cycle analysis study concluded that rooftop solar systems are more environmentally friendly than utility-scale solar installations [Mustafa Aslan 5]. Most rooftop photovoltaic (PV) systems are grid-connected power systems. Residential rooftop PV setups typically have a capacity ranging from 5 to 20 kilowatts (kW), while commercial installations often range from 100 kW to 1 megawatt (MW). As of 2022, approximately 25 million households worldwide depend on rooftop solar power [Ahlem Zegueur 6]. Currently, 15% of Chinese households use solar water heaters to heat water effectively. [7]. Hot water is an essential necessity in households, industries, hospitals, and hotels for various purposes. Previously, conventional heaters fueled by natural gas, propane, fuel oil, and electricity (primarily sourced from fossil fuels) met these demands. Due to this rise in consumption, studies predict that oil consumption will exceed 120 million barrels/day by 2025 [8]. However, widespread reliance on these conventional energy sources globally has resulted in environmental degradation and resource depletion. Furthermore, the combustion of these fuels contributes greenhouse gases such as carbon dioxide (CO_2) and nitrous oxide (N_2O) into the atmosphere, which amplify the greenhouse effect by trapping and re-radiating heat. This process contributes to an increase in the Earth's average air temperature. These greenhouse gases can persist in the atmosphere for decades to centuries, exacerbating their long-term impact on the climate. There is a pressing need to shift our energy-intensive practices towards sustainable alternatives like renewable energy. Thus, there is a growing push for the adoption and advancement of highly efficient renewable energy systems worldwide [9,10]. As a result,

in order to maintain energy security and lessen the negative effects of global warming, modern economies are increasingly relying on renewable energy sources like solar and wind power. Solar energy, due to its abundant availability, can be effectively harnessed by solar water heaters to raise the temperature of water. The fundamental elements of a solar water heating system include the collector, heat exchanger, and insulated storage tank. Solar collectors exist in three main types: flat-plate collectors (FPC), evacuated-tube collectors (ETC), and concentrated solar collector (CSC), and are used to harness solar radiation to heat water, which is then circulated through them. Among these components, the solar collector stands out as crucial within the solar water heater [11]. FPCs and ETCs are commonly employed to generate heat up to 60 °C, serving direct hot water supply and space heating needs in residential or commercial buildings [12].
This classification is depicted in figure 1.

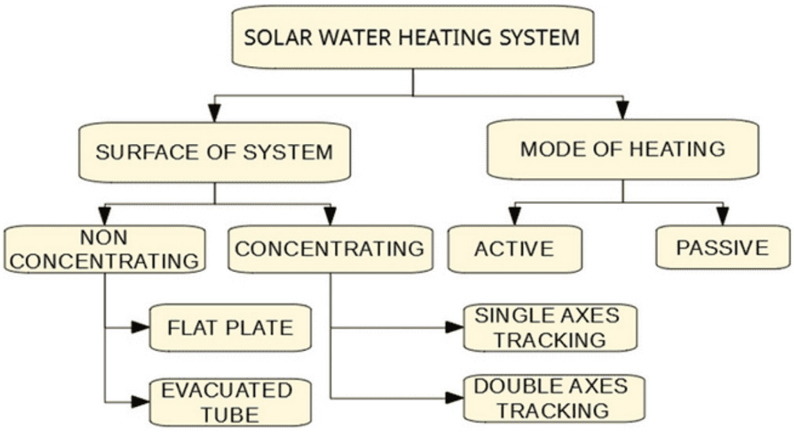

Figure 1. Classification of solar water heating systems [13].

Evacuated tube solar water collector (ETSWC) offers an advantage over flat plate solar water collector (FPSWC) in its ability to absorb heat from all directions owing to its shape, resulting in high water temperature, enhanced efficiency, and reduced heat loss coefficient [14]. ETSWC can heat the heat transfer fluid up to 150°C. Shukla et al. [15] provided an extensive discussion on solar water heating (SWH) systems, focusing on various types of solar collectors and illustrating the top 12 countries, including China and India, utilising solar water heating (SWH) systems in figure 2.

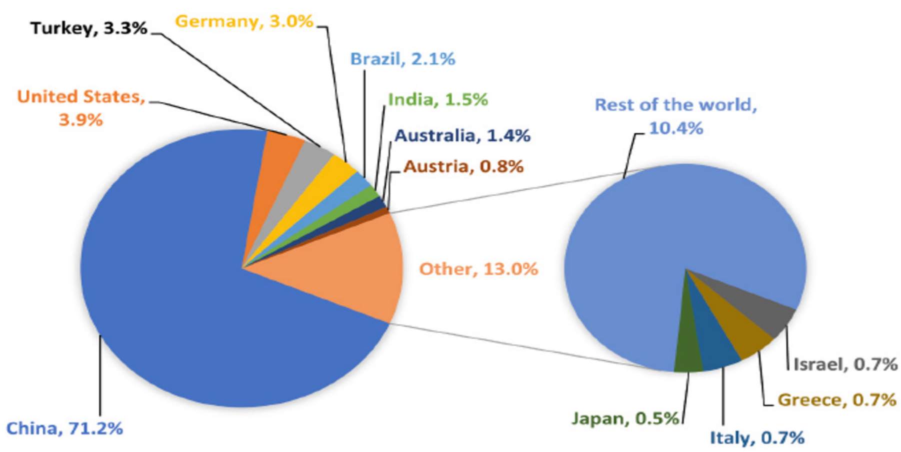

Figure 2. Implementation of SWH systems in major countries of world [16].

According to the Renewable Energy Policy Report 2019, data spanning from 2008 to 2019 indicate that China is at the forefront of SWH technology adoption.
Sokhansefat et al. [17] investigate the effectiveness of ETSC and FPSC in a cold environment condition. They found that the ETSC system outperforms the FPSC system by 41%. Additionally, they observed that weather conditions and initial temperature have a more pronounced effect on the effectiveness of FPSC compared to ETSC. Additionally, they observed that the usable energy gain for both systems diminishes with increasing input temperature, with FPSC seeing a greater decline. In cold climates, ETSC demonstrates a 30% higher annual useful energy gain compared to FPSC. Its popularity has surged due to its uncomplicated design and superior efficiency. Evacuated tube solar collectors are available in various designs, such as plain evacuated tubes, evacuated tubes equipped with heat pipes, and others. Among these, the simple and unadorned evacuated tubes are currently the most prevalent configuration. Despite their basic nature, plain evacuated tubes have been extensively employed in passively circulating solar water heating systems due to their affordability and easy installation [18,19]. To address inherent drawbacks like low performance and heat losses when not exposed to sunlight, modern solar thermal plates have undergone enhancements involving the integration of phase-changing substances and structural modifications. These improvements aim to enhance overall efficiency and mitigate inefficiencies during periods without sunlight [20,21]. Enhancing thermal efficiency typically occurs as heat transfer area and flow velocity increase, driven by higher frictional pressure drop [22]. There are many ways to enhance the performance of solar collectors. The most frequently employed strategy for improving thermal efficiency is optimising the device's structure, as shown in figure 3. The implementation of twisted and wavy tape inserts stands out as the most effective approach for enhancing the effectiveness of solar collectors across various applications, primarily because of its straightforward and cost-effective application [23]. Numerous studies have explored the impact of incorporating twisted and wavy tape into tubes on both thermal and hydraulic performance, undertaken by researchers in the field [24,25].

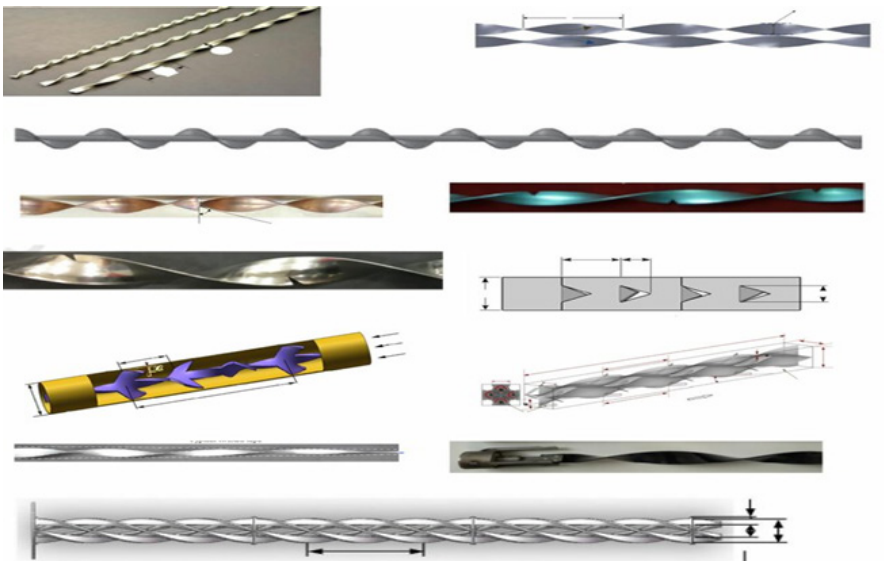

Figure 3. Different types of tapes used in previous experimental work [26].

Sundar et al. [27] utilized twisted tape (TT) inserts with varying twist ratios of 5, 10, and 15 in an FSTC. Their experiments showed that using a twist ratio of 5 resulted in an improvement of heat transfer by around 32%. Jaisankar et al. [28] conducted an experimental investigation into the impact of inserting helical twisted tapes on thermal performance and pressure drop in a water heating system that included an FSTC. Morrison et al. [29] investigated the flow of heat transfer fluid circulating within an all-glass evacuated tube (ET), resulting in disruptions to thermal inversion inside the collector tank. Additionally, they noted the presence of an inactive area towards the lower portion of the tube that adversely affects the heat collection efficiency of the water collector. Abnish et al. [14] investigated the effect of wavy and perforated wavy tapes in the flat plate collector. They found that the nusselt number is enhanced by 21% by the application of perforated wavy tape. Further, the value of maximum efficiencies obtained is 38, 50, and 55% for plain FPC, FPC with wavy tape, and FPC with perforated wavy tape, respectively.

On the other hand, Dinesh et al. [30] and Gunasekaran et al. [31] demonstrated that the effectiveness of direct flow ETSWC can be enhanced through the use of different geometric configurations, such as hetero-fused reflecting surfaces and twisted strips. They also highlighted the benefits of employing appropriate phase change materials (PCM) and absorption film coatings on the inner wall of the ET to enhance the efficiency of ETSC. Suri et al. [32] conducted a study on improving heat transfer and reducing friction in a heat exchanger tube by using twisted tape with square shaped perforation, observing a notable rise in heat transfer efficiency with this setup. On the other hand, Nanan et al. [33] examined how twisted tape with helically perforations affects heat transfer and friction loss, finding that it decreases both compared to standard helical twisted tape. However, Ponnada et al. [34] found contradictory results, stating that the use of perforated twisted tape increases both heat exchange and roughness factor in comparison to regular twisted tape. Eiamsa-Ard et al. [35] researched the impact of three distinct helical twisted tape designs on collector efficiency, establishing that the single helical twisted tape demonstrated superior performance compared to other arrangements.

Al-Fahed et al. [36] conducted an experiment in which they investigated the drop in pressure and heat transmission rate in a plain tube, micro-fine tubes, and a tube with a twist turbulator when the tube was exposed to a fluid moving laminarly. The results suggest that the highest heat transfer rate might be achieved by decreasing the twist tape ratio. Kumar et al. [37] conducted experiments to examine the effects of a performance-rated twisting tube with periphery circumferences on singles and dual V-cut forms, as well as the pressure drop and rate of heat transfer in a circular channel. They showed that the thermal performance factor increases from 1.69 to 2 when these twisted turbulators are used. Piryarungrod et al. [38] demonstrated that using taper twisted tape improves heat transmission rate, pressure variation, and overall thermal stability. Their findings indicated that a taper twisted tape with a 0.9° taper angle and a twisting ratio (3) achieved the highest thermal characteristics. Wongcharee and Eiamsa-ard [39] conducted experiments using both clockwise and counter-clockwise twisted tapes alternately in a round tube. They found that a smaller twist ratio of 3 resulted in the greatest improvement in heat transfer. Similarly, Jouybari, N. F [40] carried out a numerical analysis on fluid flow within a solar heater that included a porous substrate. They observed that increasing the thickness of the porous layer and decreasing the Darcy number led to higher fluid flow, enhanced heat transfer, and greater pressure drop.

However, another difficulty is their inability to consistently match demand and supply, largely due to their dependence on sunlight availability and heat losses. [41-43] According to recent studies [44], this problem may be successfully resolved by including an appropriate thermal storage material in the system. Phase change materials (PCMs) have many advantages, but before using any PCM in an application, important concerns including thermophysical properties, stability, and poor thermal conduction must be resolved. The major limitation observed from previous studies reveals that employing tape inserts as turbulators offers significant benefits in augmenting heat transfer rates, leading to improvements in thermal efficiency. However, research on different types of twisted and wavy tapes (WT) is lacking, despite their comparable thermo-hydraulic performance. It is also noted that the design parameters of these inserts play a crucial role in achieving optimal performance while minimising pumping power. Previous research in the field of thermal enhancement methods for evacuated tube solar collectors (ETSC) has explored various ideas in both thermal and hydraulic studies. Typically, each study has focused on investigating a single method, with only a few conducting comparative analyses involving two inserts. In this context, the objective of the current study presents a comparative analysis of three common thermal enhancement methods: the use of wavy tape inserts, perforated wavy tape with 6 mm equilateral triangles, and perforated wavy tape with 9 mm equilateral triangles. Swirl flow devices like twisted and wavy tapes are believed to enhance heat transfer through several mechanisms: (i) partitioning and obstructing the tube's section, resulting in increased flow velocity; (ii) reducing hydraulic dimensions, influencing the coefficient of heat transfer; and (iii) generating secondary fluid motion through twist mixing, enhancing convection heat transfer [14]. This unique turbulator shape significantly accelerates the heat transmission rate. As far as we are aware, there haven't been any other studies that compare these thermal augmentation techniques in the literature, and there aren't many comparison studies overall. Therefore, this work is innovative in systematically presenting a comparison among these three commonly used thermal enhancement methods. Table 1. shows the outcomes of previous research carried to enhance the performance of the collector by using various techniques.

Table 1. Shows the outcomes of previous research carried to enhance the performance of collector by using various techniques.

Authors	Modification	Working fluid	Finding
Esmail and Abughadra [45]	ETC with heat pipe	Methanol	The outcomes reveal that the ETC with heat pipe had increased efficiency than conventional collector.
Jafaryar et al. [46]	Twisted tapes with helical fins	Water-alumina grapheme	The increment of heat transfer rate is up to 70.52%
Rajan et al. [47]	Hyperbolic TT	Water	The maximum thermal performance factor is 1.171
Ebrahim et al. [48]	ETC with fin and heat pipe	Water and methanol	The ETC with water shows better results as compared to methanol as working fluid. Moreover addition of fin enhances the performances of the system.
Jin-joo [49]	Twisted tapes	Water	Thermal performance was increased by 7.7%
Murugesan et al. [50]	Wire-nails in the twisted tape with several twist ratios	Water	Thermal performance was increased up to 1.13 times compared with plain twisted tape
Chaurasia et al. [51]	Single and double strip helical screw tape inserts	Water	Nusselt number attained maximum enhancement of 112% with double strip helical screw insert than plain tube

2. EXPERIMENTAL SET UP

The installed solar water heating system consisted of an evacuated tube solar collector (ETSC) designed as a passively operated flow-through collector with eight evacuated tubes and an integrated water reservoir capable of holding 150 litres. Cold water from the storage tank enters the evacuated tubes from the upper portion, where it is evenly distributed among all tubes; the heated water is subsequently collected in the upper header and stored in the tank until equilibrium is reached between the inlet and outlet temperatures. The storage tank is constructed from steel to prevent corrosion and is insulated with polyurethane foam to minimise heat loss and maintain a constant water temperature. The tank is designed with a top lid for easy access to integrate and remove wavy tapes as shown in figures 4 and 5.

Figure 4. Isometric view of experimental setup.

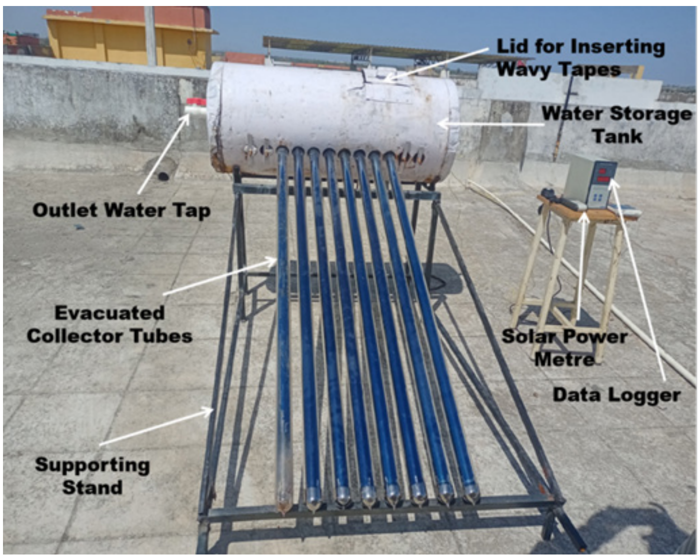

Figure 5. Image of experimental setup used in current work.

The evacuated tubes are positioned at a tilt angle of 30°, typically aligned with the local geographical latitude angle and facing south to maximise solar radiation exposure, as recommended in existing

literature[51].
Detailed technical specifications of the experimental setup can be found in Table 2.

Table 2. Physical dimension of experimental setup.

S. No.	Design material/parameters	Specification
1	Glass inclination angle	30° towards south
2	Aperture area	1.5 m2
3	Evacuated tube (8 No.s)	Internal radius 38 mm & External radius 45 mm with 1500 mm height
4	Collection tank inner dimension	400 mm diameter & 1020 mm length
5	Collection tank outer dimension	500 mm diameter & 1120 mm length
6	Insulation material	PUF of 50 mm thickness
7	Sealing Material	Silicone gel and rubber
8	Evacuated tubes material	Borosilicate glass
9	Absorptance	91 %
10	Transmittance 93%	93 %
11	Wavy tapes	Strip having dimensions of 0.3 mm thickness, 16 mm width, and a length (l) of 1200 mm.
12	Thermocouple	K type thermocouple
13	Solar radiation measurement device	Solar power metre
14	Temperature measurement device	Data logger

The copper strip used to create the wavy tapes measures 0.3 mm thick, 16 mm wide, and 1200 mm long (l). These tapes are formed by folding the strip at 20 mm intervals, each fold angled at 60°. Additionally, two variations of perforated wavy tapes are made by punching equilateral triangles, with sides measuring 6 mm and 9 mm, onto the front face of each inclined side of the wavy tape. Figure 6 illustrates the perforated wavy tapes used in the experimental setup.

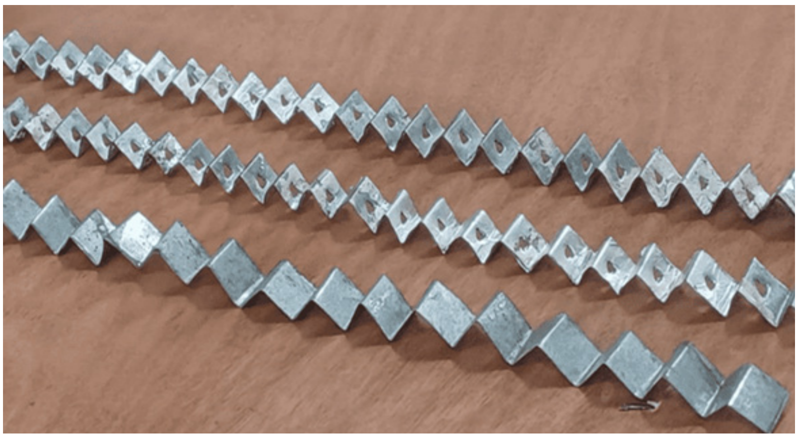

Figure 6. Perforated wavy tape used in the experimental work.

The experiments were conducted outdoors in the northern Indian climate conditions during February 2024. The experimental setup for the evacuated tube solar water heating system was installed on the flat roof of SISTec-R College in Madhya Pradesh, India (latitude 23.2599° N and longitude 77.4126° E). As discussed previously, the investigation involved four different scenarios within the ETSC. The first scenario was without any twisted tape in the tube (Without Tape), the

second scenario was with plain wavy tape in the tube (Plain WT), the third scenario involved 6 mm perforated wavy tape (PWT 6), and the fourth scenario used 9 mm perforated wavy tape (PWT 9) in the tube. Figure 5 shows the actual image of the experimental setup used in current work.
Observations were recorded over a 10-hour period for each scenario, commencing at 8 a.m. and concluding at 6 p.m. (sunset). Since the flow within the tube is bi-filamental characterized by two distinct streams: one ascending with heated fluid and the other descending with colder fluid from the reservoir, as shown in figure 7. These opposing streams coexist with a shear layer separating them. Temperature readings were taken at three different positions inside the tank, as well as at the wavy tapes in the tubes, atmospheric temperature, and solar intensity, all measured hourly throughout the experiment. Subsequent calculations were conducted to perform energetic and exergetic analyses of the four scenarios.

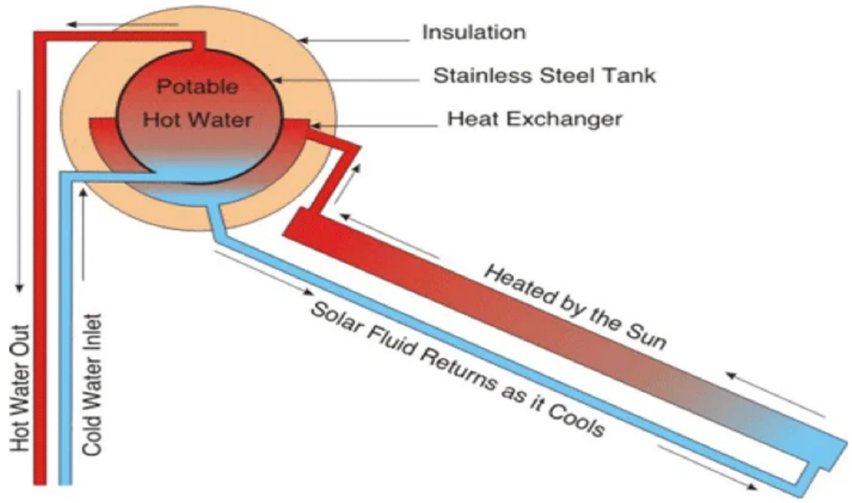

Figure 7. Flow pattern in an evacuated tube heated [52].

A total of six K-type thermocouples were fitted to monitor temperatures in different places. The bulk water temperature was determined by averaging the readings from three thermocouples that were positioned within the water tank at the top, bottom, and halfway between the three points. One thermocouple was used outside to detect the ambient temperature, and two thermocouples were positioned within the evacuated tube to measure the temperature of the wavy tape. A data logger was used to record and store temperature measurements from these thermocouples.
Solar radiation was measured using a solar power metre with a reading accuracy of ±10.0 W/m2. To assure measurement reproducibility, each experiment was run for at least 5 clear-sky solar days; subsequently, readings from similar solar days with comparable radiation patterns were analysed to estimate the efficiency of the ETSC. Uncertainties may arise in experiments due to various factors, such as inaccuracies in measurement tools, calibration, and data processing errors. In this particular experiment, thermocouples were employed to measure temperature with an uncertainty of 0.75, while a solar power metre, with a potential uncertainty of 4.0 as indicated in the instruction book, was used to monitor solar radiation. The standard uncertainty in the experiment can be calculated using the formula outlined by khan et al. [53].

$$UC_z = \sqrt{\frac{\sum_{n=} (z_n - z_m)}{n -}} \qquad (\ )$$

Where UC_z indicates uncertainty value, Z_n and Z_m are the individual and mean values of three readings, respectively, n is total number of measurements.

3. DATA REDUCTION

3.1. Energy Analysis

The primary focus of the initial law examination revolves around quantifying the efficiency of energy conversion within a thermodynamic system. The efficiency, as expressed by the first law, is given below [54,55].

$$\eta_{energy} = \frac{Q_w}{Q_{in}} \quad (2)$$

Where, Q_w is the energy contained within the water and Q_{in} represent the amount of solar energy acquired by the tubes.

Moreover, the energy contained within the water can be computed using the equations provided by Kumar and Mylsamy [56].

$$Q_w = m_w C_{p,w}(T_{wout} - T_{win}) \quad (3)$$

m_w and $C_{p,w}$ is the mass flow rate (kg/s) and specific heat values of water in the collection tank whereas T_{Wout} and T_{Win} is the water temperature at outlet and inlet section in °C.

The thermal energy absorbed by evacuated tubes during a specific period has been derived from the below equation :

$$Q_{in} = A_c \times I_t \quad (4)$$

Where A_c (m^2) is the aperture area and I_t is the amount of solar radiation incident on the tubes in W/m^2.

3.2. Exergy Analysis

The best way to measure the inefficiencies in a solar heating system induced by thermal irreversibility is to evaluate the system's energetic and exergetic effectiveness. Exergy serves as a measure of the maximum potential performance achievable by any thermal system when it reaches thermal equilibrium conditions.

$$\eta_{exe} = \frac{E_{x,out}}{E_{x,inp}} \quad (5)$$

$E_{x,out}$ stands for the water's usable exergy and is computed as [57].

$$E_{x,out} = m_w \times C_{p,w}\left[(T_{wout} - T_{win}) - T_a\, ln(\frac{T_{wout}}{T_{winp}})\right] \quad (6)$$

The exergy absorbed is given by [58].

$$E_{x,inp} = A_c \times I_t\left[1 + \frac{1}{3}\times\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\times\left(\frac{T_a}{T_s}\right)\right] \quad (7)$$

Where T_s represents the sun's temperature and equal to 5760 K.

4. RESULT AND DISCUSSION

In this present study, a comparative experimental investigation of the developed system has been conducted in four distinct cases within the ETSC. The first case was without any twisted tape in the tube (without tape), the second was with plain wavy tape in the tube (plain WT), the third involved 6 mm perforated wavy tape (PWT 6), and the fourth used 9 mm perforated wavy tape (PWT 9) in the tube. Utilizing experimental data, a thermal performance analysis of the developed system was performed using the equations previously discussed. This section delves into the analysis of parameters such as inlet temperature, ambient temperature, outlet temperature, and variations in solar radiation across different scenarios. Additionally, this section also presents a comparative analysis of energy efficiency and exergy efficiency corresponding to the various scenarios.

Figure 8 shows the time wise fluctuation of solar radiation and ambient temperature at every 1 hr interval from 9th to 12th February 2024, in the city of Bhopal, Madhya Pradesh, India (latitude 23.2599° N and longitude 77.4126° E). The four different cases of the experiment were carried out on four different days, starting from 9th February to 12th February 2024. Initially, solar radiation exhibited an upward trend over time, peaking at 960 W/m2 around 13 hours before gradually declining. The hourly variations in ambient temperature are also depicted, showing a range from 17°C at 8 hours to a peak of 34°C at 16 hours.

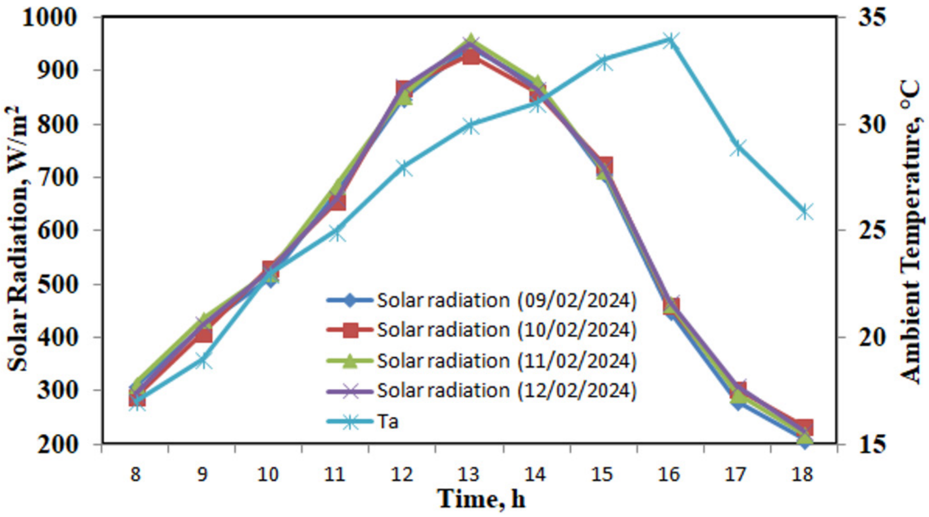

Figure 8. Time wise fluctuation of solar radiation and ambient temperature.

4.1. Temperature variation

The graphical representation in figure 9 and figure 10 below illustrates the hourly changes in outlet temperature and temperature difference both with and without wavy tapes.

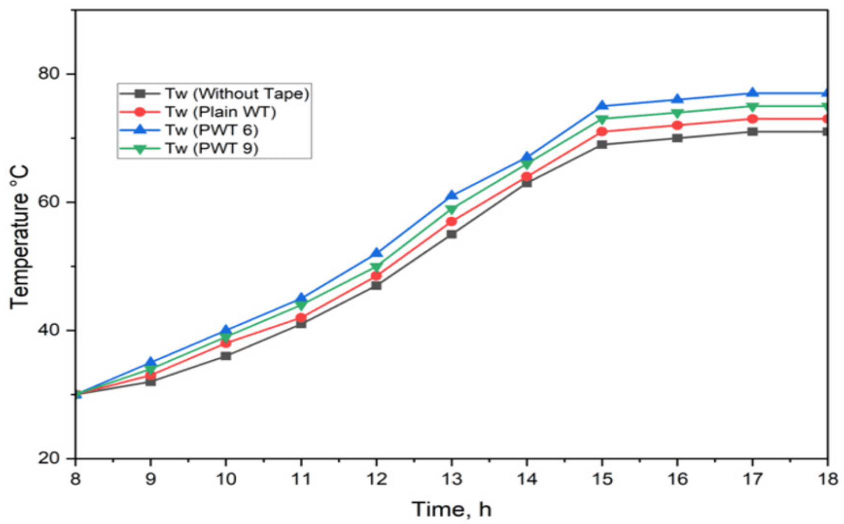

Figure 9. Time wise fluctuation of outlet water temperature of different tested cases.

The tank water temperature exhibits a similar trend across all operational modes, including those without any wavy tapes (Without Tape), with plain wavy tape (Plain WT), and with perforated wavy tapes of two different perforation sizes (PWT 6 and PWT 9), as depicted in Figure 10. The temperature is measured at three different locations within the tank (top, centre, and bottom) during the testing. The average of these three temperatures is taken as the outlet in the analysis portion. The highest outlet water temperature was recorded in the ETSC with 6 PWT (77 °C), significantly surpassing the ETSC without WT (70 °C), ETSC with plain WT (73 °C), and the ETSC with 9 PWT (75 °C). This clearly indicates that the presence of wavy tapes induces turbulent flow within the ETC tubes, facilitating better mixing of the tube water to capture maximum solar energy as useful heat.

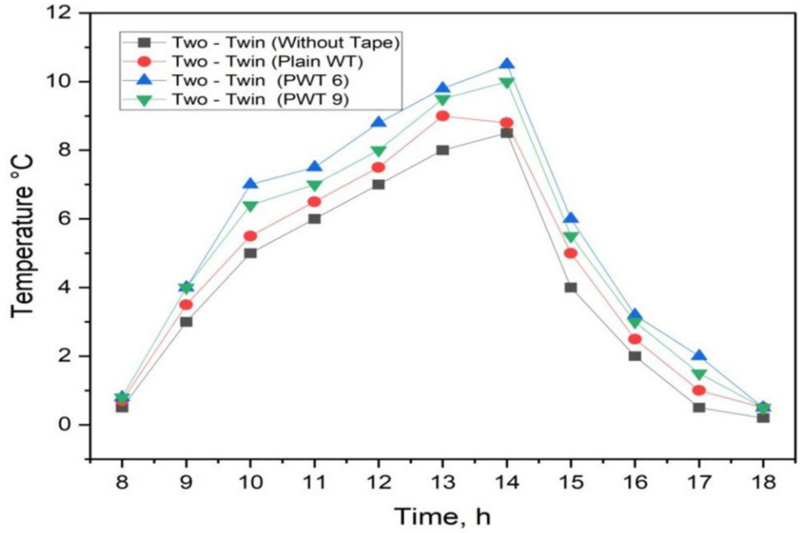

Figure 10. Time wise fluctuation of water temperature difference of different tested cases.

Figure 11 also illustrates the temperature variation at the central portion during the testing day of the evacuated tube under various operational modes, both with and without wavy tape arrangements. The water temperature at the tube's center remains consistently higher, primarily because this part receives direct exposure to solar radiation throughout the day.

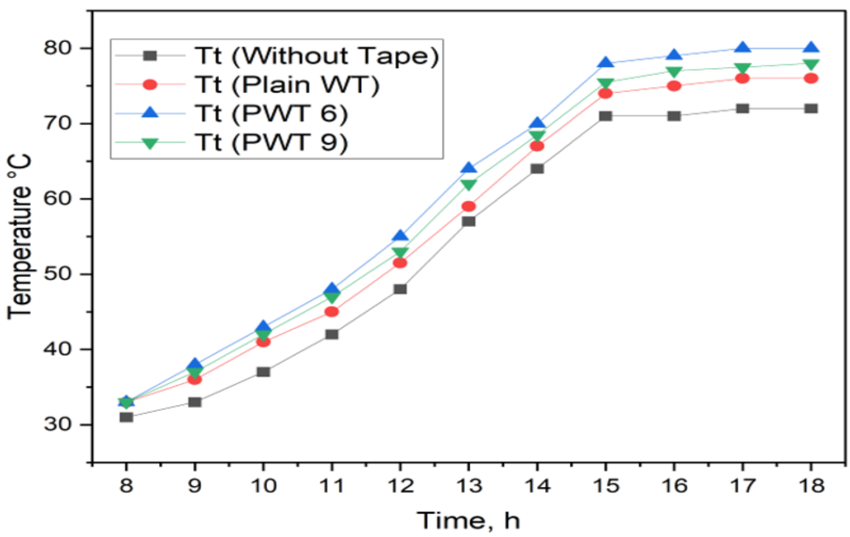

Figure 11. Time wise fluctuation of water temperature in the central portion of the evacuated tube of different tested cases.

The incorporation of wavy tapes generates secondary flow compared to FPC without WT, thereby enhancing water temperature. Perforations in the tape intensify flow mixing, creating more intense turbulence and swirl flow than plain wavy tape [57]. Consequently, there is an increase in secondary flow velocity and improved mixing between the tube's core and adjacent wall, enhancing convective heat transport. However, larger perforation sizes may reduce turbulence, impacting system performance accordingly. Therefore, wavy tapes with smaller sizes are recommended for better heat transfer characteristics.

4.2. Hourly Energy Storage

Figure 12 depicts the amount of energy stored in the water tank of the ETC solar water heating system in the form of sensible heat.

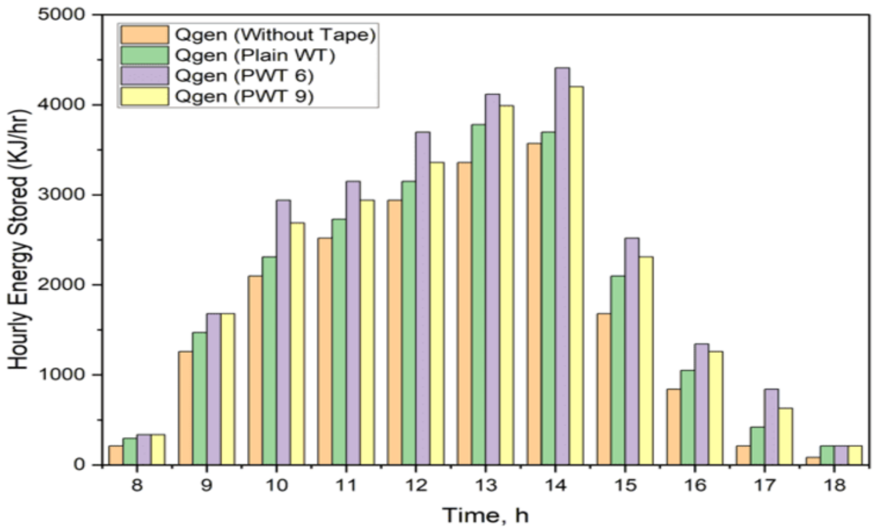

Figure 12. Hourly energy stored in water tank of ETSC with different wavy tapes.

The energy stored gradually increased in the morning and reached its highest point by the afternoon at 14:00 hours. The minimum stored energy was observed in the evening at 18:00 hours when solar insolation was at its lowest. It is evident that the maximum energy was recovered by 14:00 hours, during all operational modes. The highest energy stored in the collection tank was recorded in the ETSC with 6 PWT (4410 KJ/hr), significantly surpassing the ETSC without WT (3570 KJ/hr), ETSC with plain WT (3696 KJ/hr), and ETSC with 9 PWT (4200 KJ/hr). It also reveals that the maximum energy storage of ETSC with 6 PWT was higher than that of ETSC without WT, ETSC with plain WT, and ETSC with 9 PWT by 24, 19.5, and 5.5%, respectively. This clearly indicates that the presence of wavy tapes induces turbulent flow within the ETC tubes, facilitating better mixing of the tube water to capture maximum solar energy as useful heat.

4.3. Energetic Analysis

Figure 13 illustrates the average change in energy efficiency of the water heating system with varying solar intensity at hourly intervals during simultaneous operation using wavy tape and perforated wavy tapes.

The peak hourly efficiency was observed around 14:00 hours across all experimental cases. The highest hourly efficiency was recorded as 83.33% for the ETSC with 6 PWT, followed by 81.87%, 78.31%, and 75.64% for the ETSC with 9 PWT, ETSC with plain WT, and ETSC without WT, respectively.

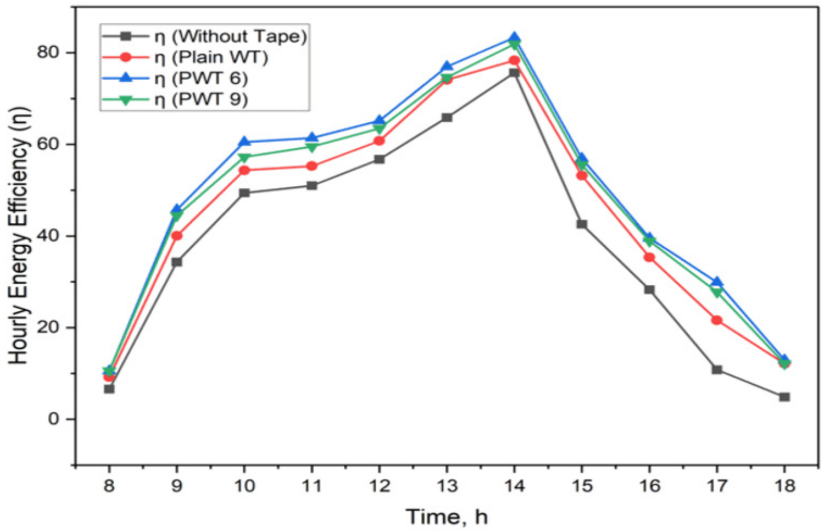

Figure 13. Time wise fluctuation of energy efficiency of ETSC with different wavy tapes.

Moreover, it is evident that the water collector with perforated wavy tape consistently exhibits higher efficiency compared to a collector without wavy tape. This is because the generation of swirl flow in a wavy tape collector enhances convective heat transfer, thereby improving thermal performance. In contrast, without wavy tape, swirl flow is not generated in the collector, leading to reduced heat transfer and lower efficiency. Figure 14 demonstrates the daily energy efficiency achieved for the different cases of the experiment. Furthermore, it was noticed that the effect of perforated wavy tape ETSC (6 PWT) exhibits an average energy efficiency of 49.36%, which is higher than without WT (38.72%), with plain WT (44.93%), and with 9 PWT (47.82%).

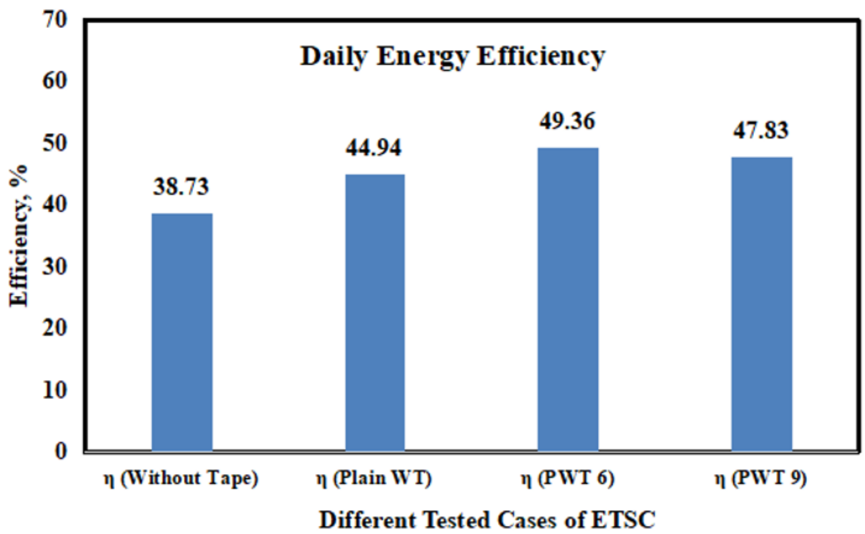

Figure 14. Daily energy efficiency for the different cases of the experiment.

It was observed that the average energy efficiency of ETSC with 6 PWT was higher by 27.5, 9.84, and 3.5% compared to without WT, with plain WT, and with 9 PWT, respectively. The collector fitted with wavy tape having a 6 mm hole achieves the highest efficiency for the same solar radiation value because the most swirl production occurs in this situation, which would maximize heat transfer and hydraulic fluid travel distance. The swirl production diminishes with increasing perforated size, which would reduce heat transmission and thermal efficiency. The findings of the current study match the work carried out by Vijay et al. [58] which reveals that when combined with twisted tape, a flat-plate solar collector has an efficiency rating of 66% and an efficiency rating of 48%. A similar work was also carried out by Gunasekaran et al. [27] in which the thermal efficiency of ETSC was increased by 6.8% incorporating twisted tape with a twist ratio of 2 and 4.6% with twist ratio of 3.

4.4. Exergetic Analysis

The efficiency based on the second law was determined by evaluating the exergy within the thermodynamic system concerning reference atmospheric conditions, reflecting the quality of energy availability. While energy remains conserved, exergy is accrued over time. A higher exergy efficiency signifies superior system performance at a higher level. Figure 15 illustrates the average change in exergy efficiency of the water heating system with varying solar intensity at hourly intervals during simultaneous operation using wavy tape and perforated wavy tapes. The peak hourly efficiency was observed around 14:00 hours across all experimental cases. The highest hourly efficiency was recorded as 83.33% for the ETSC with 6 PWT, followed by 9.83%, 8.34%, and 7.87% for the ETSC with 9 PWT, ETSC with plain WT, and ETSC without WT, respectively.

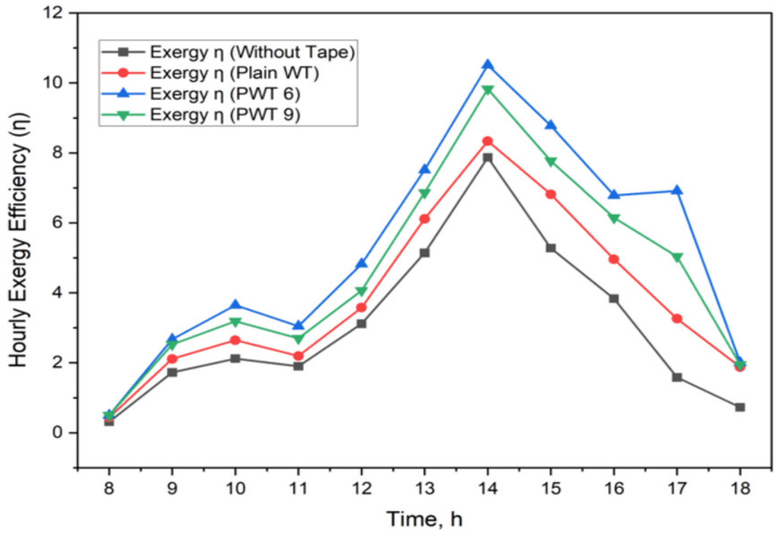

Figure 15. Time wise fluctuation of exergy efficiency of ETSC with different wavy tapes.

Figure 16 demonstrates the daily exergy efficiency achieved for the different cases of the experiment.

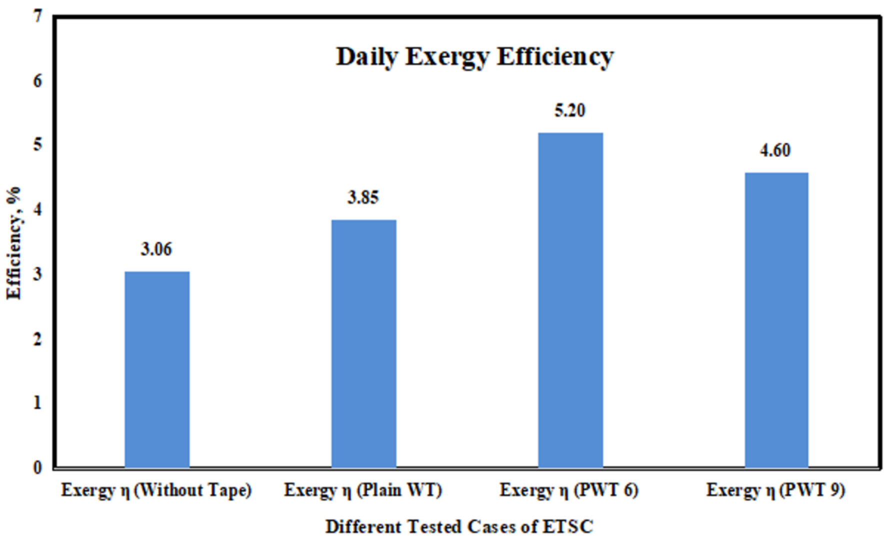

Figure 16. Daily exergy efficiency for the different cases of the experiment.

Furthermore, it was noticed that the effect of perforated wavy tape ETSC (6 PWT) exhibits an average exergy efficiency of 5.2%, which is higher than without WT (3.06%), with plain WT (3.84%), and with 9 PWT (4.59%). It was observed that the average exergy efficiency of ETSC with 6 PWT was higher by 70.18, 35.11, and 13.1% compared to without WT, with plain WT, and with 9 PWT, respectively.

5. CONCLUSION

The experimental study in cold climatic conditions is conducted to compare the effects of wavy tape and perforated wavy tapes on the energy and exergy analysis of an evacuated tube solar water heating (ETC) system. The purpose of this work is to assess the enhancement in thermal performance of the system. The association of wavy tapes is believed to enhance heat transfer through partitioning and obstructing the tube's section, resulting in increased flow velocity, while the perforations boost turbulence and swirl in the evacuated tube. The first law of thermodynamics focuses on energy quantity and tracks changes in a system's energy, without considering energy quality. Therefore, energy and exergy analyses are crucial tools for evaluating performance. The following conclusions were drawn from the experimental work:

- The tank water temperature was enhanced by 7 °C, 4 °C, and 2 °C by the incorporation of wavy tape with 6 mm perforation, wavy tape with 9 mm perforation, and plain wavy tape, respectively in the evacuated tube solar water heater.
- The solar energy recovery by the ETC solar water heaters was improved by the incorporation of wavy tapes, as the wavy tapes result in reducing hydraulic dimensions, influencing the coefficient of heat transfer, generating secondary fluid motion through twist mixing, and enhancing convection heat transfer.
- The highest energy stored in the collection tank was recorded in the ETSC with 6 PWT (4410 KJ/hr), significantly surpassing the ETSC without WT (3570 KJ/hr), ETSC with plain WT (3696 KJ/hr), and ETSC with 9 PWT (4200 KJ/hr).
- The maximum energy storage of ETSC with 6 PWT was higher than that of ETSC without WT, ETSC with plain WT, and ETSC with 9 PWT by 24, 19.5, and 5.5%, respectively.
- The highest hourly efficiency was recorded as 83.33% for the ETSC with 6 PWT, followed by 81.87%, 78.31%, and 75.64% for the ETSC with 9 PWT, ETSC with plain WT, and ETSC without WT, respectively.
- The effect of perforated wavy tape ETSC (6 PWT) exhibits an average energy efficiency of 49.36%, which is higher than without WT (38.72%), with plain WT (44.93%), and with 9 PWT (47.82%).
- The average energy efficiency of ETSC with 6 PWT was higher by 27.5, 9.84, and 3.5 % compared to without WT, with plain WT, and with 9 PWT, respectively. This shows that modifying the wavy tape, particularly by perforating it, increases turbulent kinetic energy, leading to a significant rise in water temperature and resulting in higher energy efficiency.
- The average exergy efficiency of ETSC with 6 PWT was higher by 70.18, 35.11, and 13.1% compared to without WT, with plain WT, and with 9 PWT, respectively.
- The performance of ETSC can also be improved by using wavy tapes of different configurations and perforations to generate more turbulence as the fluid flows through the tube. The integration of PCM in the storage tank can enhance the overall performance of the system.

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REFERENCES

[1].Boafo, F.E., Kim, J.T. & Kim, J.H. (2017) Evaluating the impact of green roof evapotranspiration on annual building energy performance. International Journal of Green Energy, 14, 479–489. DOI: 10.1080/15435075.2016.1278375.

[2].Sofiane, M. I. H. O. U. B., & Abdelilah, B. E. N. A. H. M. E. D. (2024). Predicting the Impact of Different Cooling Systems on the Performance of Parabolic Trough Concentrating Solar Plant based on Real Data. Solar Energy and Sustainable Development Journal, 13(2), 264-285.

[3].Reddy, P., Gupta, M.V.N.S., Nundy, S., Karthick, A. & Ghosh, A. (2020) Status of BIPV and BAPV system for less energy-hungry building in India—A review. Applied Sciences, 10, 2337. DOI: 10.3390/app10072337.

[4].Pasupathi, M.K., Alagar, K. MMM & Aritra, G. Characterization of hybridnano/paraffin organic phase change material for thermal energy storage applications in solar thermal systems, Energies 13–19 (2020) 5079. https://doi. DOI: 10.3390/en13195079.

[5].Aslan, M., Afif, B., Salmi, M., Merabet, B., Berka, M., & Masoud, S. (2025). Performance Enhancement of Microgrid Systems Using Backstepping Control for Grid Side Converter and MPPT Optimization. Solar Energy and Sustainable Development Journal, 14(1), 19-41.

[6].Ahlem Z., Toufik S., Abderrezak M. (2024). Optimizing a Sustainable Power System with Green Hydrogen Energy Storage for Telecommunication Station Loads. Solar Energy and Sustainable Development Journal, 14(1), 19-41.

[7].Saed, J., Abdunnabi, M., Essnid, A., & Buishi, A. (2017). New designed thermosyphon solar water heater with small sized parabolic trough collectors. Solar Energy and Sustainable Development Journal, 6(2), 30-41.

[8].Ramasamy, K.K. & Srinivasan, P.S.S. (2012) Experimental investigation of forced and wind assisted domestic solar hot water systems. Proceedings of the Institution of Mechanical Engineers, Part C, 226, 154–160. DOI: 10.1177/0954406211413962.

[9].Agrawal, R. & Singh, K.D.P. (2021) Performance evaluation of double slope solar still augmented with binary eutectic phase change material and steel wool fibre, Sustainable Energy. Technology Assessment, 48, 101597.

[10]. Nikhil Babu, P., Mohankumar, D., Manoj Kumar, P., Makeshkumar, M., Gokulnath, M., Gurubalaji, K., Harrish, G. & Ashok, M. (2021) Energy efficient refrigeration system with simultaneous heating and cooling. Materials Today: Proceedings, 45, 8188–8194. DOI: 10.1016/j.matpr.2021.03.072.

[11]. Abdunnabi, M., Abusalama, A., Algamil, M., & Almontaser, M. (2018). Flat Plate based-Solar System with a tracking system. Solar Energy and Sustainable Development Journal, 7(1), 24-37.

[12]. Algareu, A., Abdunnabi, M., Mabruk, M., & Elmaghrabi, A. M. (2021). Legionella bacteria activity investigation in domestic water heating systems: Tripoli-Libya as a case study. Solar Energy and Sustainable Development Journal, 10(2), 11-20.

[13]. Kumar, A., Said, Z. & Bellos, E. (2021) An up-to-date review on evacuated tube solar collectors. Journal of Thermal Analysis and Calorimetry, 145, 2873–2889. DOI: 10.1007/s10973-

020-09953-9.

[14]. Kumar, A., Singh, K. D. P., & Agrawal, R. (2024). Intensification of thermal characteristics of flat plate solar water heater using triangular perforated wavy tape. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 09544062241242589.

[15]. Shukla, R. & Sumathy, K. P, Erickson J, gong. Recent advances in the solar water heating systems: A review. Renewable and Sustainable Energy Reviews, 2013, 173–190.

[16]. Kumar, B., Srivastava, G. P., Kumar, M., & Patil, A. K. (2018). A review of heat transfer and fluid flow mechanism in heat exchanger tube with inserts. Chemical Engineering and Processing-Process Intensification, 123, 126-137.

[17]. Sokhansefat, T., Kasaeian, A., Rahmani, K., Heidari, A.H., Aghakhani, F. & Mahian, O. (2018) Thermoeconomic and environmental analysis of solar flat plate and evacuated tube collectors in cold climatic conditions. Renewable Energy, 115, 501–508. DOI: 10.1016/j.renene.2017.08.057.

[18]. Touaba, O., Ait Cheikh, M.S., Slimani, M.E.A., Bouraiou, A., Ziane, A., Necaibia, A. & Harmim, A. (2020) Experimental investigation of solar water heater equipped with a solar collector using waste oil as absorber and working fluid. Solar Energy, 199, 630–644. DOI: 10.1016/j.solener.2020.02.064.

[19]. Taamneh, Y., Manokar, A.M., Thalib, M.M., Kabeel, A.E., Sathyamurthy, R. & Chamkha, A.J. (2020) Extraction of drinking water from modified inclined solar still incorporated with spiral tube solar water heater. Journal of Water Process Engineering, 38, 101613. DOI: 10.1016/j.jwpe.2020.101613.

[20]. Saravanakumar, P.T., Arunkumar, S.P., Brailson Mansingh, B., Kumar, P.M., Ram Subbiah, E. & V.K. (2021) Investigating the effect of thermal cycling on thermal characteristics of the nano-silica based phase changing material (PCM). Materials Today: Proceedings. DOI: 10.1016/j.matpr.2021.09.095.

[21]. King, M.F.L., Rao, P.N., Sivakumar, A., Mamidi, V.K., Richard, S., Vijayakumar, M., Arunprasath, K. & Kumar, P.M. (2022) Thermal performance of a double-glazed window integrated with a phase change material (PCM). Materials Today: Proceedings, 50, 1516–1521. DOI: 10.1016/j.matpr.2021.09.099.

[22]. Iman, P. (2022) Using Rooftop Solar Heating to Supply Part of a High-Rise Residential Building Heat in the Cold Climate of Iran: One-Year Dynamic Analysis. International Transactions on Electrical Energy Systems, 2022.1, 9982264.

[23]. Omeiza, L. A., Abid, M., Dhanasekaran, A., Subramanian, Y., Raj, V., Kozak, K., ... & Azad, A. K. (2023). Application of solar thermal collectors for energy consumption in public buildings–An updated technical review. Journal of Engineering Research.

[24]. Omidi, M., Farhadi, M. & Jafari, M. (2017) A comprehensive review on double pipe heat exchangers. Applied Thermal Engineering, 110, 1075–1090. DOI: 10.1016/j.applthermaleng.2016.09.027.

[25]. Balaji, K., Ganesh Kumar, P.G., Sakthivadivel, D., Vigneswaran, V.S. & Iniyan, S. (2019) Experimental investigation on flat plate solar collector using frictionally engaged thermal performance enhancer in the absorber tube. Renewable Energy, 142, 62–72. DOI: 10.1016/j.renene.2019.04.078.

[26]. Liu, S. & Sakr, M. (2013) A comprehensive review on passive heat transfer enhancements in pipe exchangers. Renewable and Sustainable Energy Reviews, 19, 64–81. DOI: 10.1016/j.rser.2012.11.021.

[27]. Sundar, L.S., Singh, M.K., Punnaiah, V. & Sousa, A.C.M. (2018) Experimental investigation

of Al2O3/water nanofluids on the effectiveness of solar flat-plate collectors with and without twisted tape inserts. Renewable Energy, 119, 820–833. DOI: 10.1016/j.renene.2017.10.056.

[28]. Jaisankar, S., Radhakrishnan, T.K. & Sheeba, K.N. (2009) Experimental studies on heat transfer and friction factor characteristics of forced circulation solar water heater system fitted with helical twisted tapes. Solar Energy, 83, 1943–1952. DOI: 10.1016/j.solener.2009.07.006.

[29]. Morrison, G.L., Budihardjo, I. & Behnia, M. (2004) Water-in-glass evacuated tube solar water heaters. Solar Energy, 76, 135–140. DOI: 10.1016/j.solener.2003.07.024.

[30]. Dinesh, S.N., Ravi, S., Manoj Kumar, P., Subbiah, R., Karthick, A., Saravanakumar, P.T. & Aravinth Pranav, R. (2021) Study on an ETC solar water heater using flat and wavy diffuse reflectors. Materials Today: Proceedings, 47, 5228–5232. DOI: 10.1016/j.matpr.2021.05.561.

[31]. Gunasekaran, N., Manoj Kumar, P., Raja, S., Sharavanan, S., Avinas, K., Aakash Kannan, P. & Gokul, S. (2021) Investigation on ETC solar water heater using twisted tape inserts. Materials Today: Proceedings, 47, 5011–5016. DOI: 10.1016/j.matpr.2021.04.586.

[32]. Suri, A.R.S., Kumar, A. & Maithani, R. (2018) Convective heat transfer enhancement techniques of heat exchanger tubes: A review. International Journal of Ambient Energy, 39, 649–670. DOI: 10.1080/01430750.2017.1324816.

[33]. Nanan, K., Wongcharee, K., Nuntadusit, C. & Eiamsa-ard, S. (2012) Forced convective heat transfer by swirling impinging jets issuing from nozzles equipped with twisted tapes. International Communications in Heat and Mass Transfer, 39, 844–852. DOI: 10.1016/j.icheatmasstransfer.2012.05.002.

[34]. Ponnada, S., Subrahmanyam, T. & Naidu, S.V. (2019) A comparative study on the thermal performance of water in a circular tube with twisted tapes, perforated twisted tapes and perforated twisted tapes with alternate axis. International Journal of Thermal Sciences, 136, 530–538. DOI: 10.1016/j.ijthermalsci.2018.11.008.

[35]. Eiamsa-Ard, S., Nanan, K., Wongcharee, K., Yongsiri, K. & Thianpong, C. (2014b) Thermohydraulic performance of heat exchanger tube twisted tapes thermohydraulic performance of heat exchanger tube equipped with single-. Double Triple-Helical Twisted Tapes;37-41. DOI: 10.1080/00986445.2013.858038.

[36]. Al-Fahed, S., Chamra, L.M., & Chakroun W. (1998) Pressure drop and heat transfer comparison for both microfin tube and twisted-tape inserts in laminar flow. Exp Therm Fluid Sci, 18, 323–333.

[37]. Kumar, B., Patil, A.K., Kumar, M. (2020) Performance enhancement by perforated twisted tape tube insert with single and double v cuts in a heat exchanger tube. Heat Transf Re 51, 395–406.

[38]. Piriyarungrod, N., Eiamsa-Ard, S., Thianpong, C., Pimsarn, M., & Nanan, K. J. C. E. (2015). Heat transfer enhancement by tapered twisted tape inserts. Chemical Engineering and Processing: Process Intensification, 96, 62-71.

[39]. Wongcharee, K. and Eiamsa-Ard, S. (2011) Heat transfer enhancement by twisted tapes with alternate-axes and triangular, rectangular and trapezoidal wings. Chemical Engineering and Processing: Process Intensification, 50(2), 211-219.

[40]. Jouybari, N.F. & Lundström, T.S. (2020) Performance improvement of a solar air heater by covering the absorber plate with a thin porous material. Energy, 190, 116437.

[41]. Papadimitratos A, Sobhansarbandi S, Pozdin V, Zakhidov A, Hassanipour F. (2016) Evacuated tube solar collectors integrated with phase change materials. Sol Energy, 129:10-19.

[42]. Krishnavel, V., Karthick, A. & Murugavel, K.K. (2014) Experimental analysis of concrete

absorber solar water heating systems. Energy and Buildings, 84, 501–505. DOI: 10.1016/j.enbuild.2014.08.025.

[43]. Tang, R. & Yang, Y. (2014) Nocturnal reverse flow in water-in-glass evacuated tube solar water heaters. Energy Conversion and Management, 80, 173–177. DOI: 10.1016/j.enconman.2014.01.025.

[44]. Agrawal, R., Singh, K.D.P., Paswan, M.K. (2020) Review on Enhancement of Thermal Conductivity of Phase Change Materials with Nano-Particle in Engineering Applications. Materials Today: Proceedings, 22, 1617–1627.

[45]. Ismail, K.A.R. & Abogderah, M.M. (1998) Performance of a heat pipe solar collector. Journal of Solar Energy Engineering. Transaction Publishing of ASME, 120, 51–59. DOI: 10.1115/1.2888047.

[46]. Jafaryar, M., Said, Z. & Sheikholeslami, M. (2022) Hybrid nanofluid turbulent transportation through a tube with an innovative twisted tape combined with helical fins heat sink. Sustainable Energy Technologies and Assessments, 53, 102–702. DOI: 10.1016/j.seta.2022.102702.

[47]. Rajan, A. & Prasad, L. (2022) Performance investigation of heat exchanger tube fitted with hyperbolic-cut twisted tape in turbulent flow. Proceedings of the Institution of Mechanical Engineers, Part C, 236, 8134–8149. DOI: 10.1177/09544062221085102.

[48]. Brahim, T., Dhaou, M.H. & Jemni, A. (2014) Theoretical and experimental investigation of plate screen mesh heat pipe solar collector. Energy Conversion and Management, 87, 428–438. DOI: 10.1016/j.enconman.2014.07.041.

[49]. Joo, H.J., Kwak, H.Y. & Kong, M. (2022) Effect of twisted tape inserts on thermal performance of heat pipe evacuated-tube solar thermal collector. Energy, 254, 124307. DOI: 10.1016/j.energy.2022.124307.

[50]. Murugesan, P., Mayilsamy, K. & Suresh, S. (2010) Heat Transfer and friction factor studies in a circular tube fitted with twisted tape consisting of wire-nails. Chinese Journal of Chemical Engineering, 18, 1038–1042. DOI: 10.1016/S1004-9541(09)60166-X.

[51]. Chaurasia, S.R. & Sarviya, R. (2021) Numerical and experimental thermal performance with entropy generation analysis on tube with helical screw tape inserts at number of strips in turbulent flow. Proceedings of the Institution of Mechanical Engineers, Part C, 235, 1057–1070. DOI: 10.1177/0954406220937734.

[52]. Budihardjo, I. Evacuated Tubular Solar Water Heaters (Doctoral dissertation, UNSW Sydney) (2005).

[53]. Khan, M. M. A.; Ibrahim, N. I.; Saidur, R.; Mahbubul, I. M.; Al-Sulaiman, F. A. Performance Assessment of a Solar Powered Ammonia–Water Absorption Refrigeration System with Storage Units. Energy Convers. Manag. 2016, 126, 316–328.

[54]. Bracamonte, J., Parada, J., Dimas, J. & Baritto, M. (2015) Effect of the collector tilt angle on thermal efficiency and stratification of passive water in glass evacuated tube solar water heater. Applied Energy, 155, 648–659. DOI: 10.1016/j.apenergy.2015.06.008.

[55]. Li, F.F., Diao, Y.H., Zhao, Y.H., Zhu, T. & Liu, J. (2016) Experimental study on the thermal performance of a new type of thermal energy storage based on flat micro-heat pipe array. Energy Conversion and Management, 112, 395–403. DOI: 10.1016/j.enconman.2016.01.039.

[56]. Manoj Kumar, P.M. & Mylsamy, K. (2019) Experimental investigation of solar water heater integrated with a nanocomposite phase change material. Journal of Thermal Analysis and Calorimetry, 136, 121–132. DOI: 10.1007/s10973-018-7937-9.

[57]. Petela, R. (2003) Exergy of undiluted thermal radiation. Solar Energy, 74, 469–488. DOI: 10.1016/S0038-092X(03)00226-3.

[58]. Vijay, R., Vijayakumar, P., Kumaresan, G. (2021) Performance study of flat plate solar collector integrated with twisted tape inserts. Materials Today: Proceedings, 45:1222-1226.