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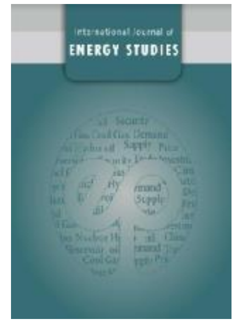

Research Article

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Experimental Study on Using Two Types of Square Tube Absorbers and Distilled Water Coolant in a Photovoltaic Thermal Collector (Pv/T)

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Highlights:

- The thermal and electrical energies of serpentine and head & riser heat exchangers by distilled water were calculated.
- The overall energetic efficency increment was investigated.
- The thermal performance of both heat exchangers was investigated.

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ABSTRACT

Several recently conducted studies have focused on different technologies that have been tested for improving photovoltaic (PV) modules' performances and increasing the performances of solar systems. One of the most important of these techniques is the development of a heat exchanger design. According to extensive literature reviews, most photovoltaic panels use circular tubes, through which, water flows to carry out the cooling process. In the current experimental study, a different design has been applied, and square tubes have been used for increasing the panel-cooling tubes' contact area. The hybrid photovoltaic thermal (PV/T) module's performance has been evaluated and compared using a square-shaped copper tube in two types of heat exchangers, serpentine and head & riser (PV/T_S and PV/$T_{H\&R}$). At flow rates 0.5 and 1 L/m, outdoor experiments were conducted during August 2019 in Karabük city, Turkey. Results show that in case of PV/T modules, the overall efficiency value was maximum 48.6% at 0.5 L/m while its average value was 59.4% at 1 L/m for serpentine heat exchanger. The mentioned values were 41.7% at 0.5 L/m and 54.7% at 1 L/m for head & riser heat exchanger, respectively. Furthermore, from the perspective of energy, the serpentine heat exchanger design with flow rate 1L/m showed better photovoltaic energy conversion in comparison with other designs and flow rates.

Keywords: *Photovoltaic Thermal Unit PV/T, Serpentine, Head and Riser*

1. INTRODUCTION

During the last few decades, researchers have been interested in renewable energy systems, specifically solar energy, which is considered as a source of clean and cheap energy. Nearly 81% solar radiation, which is concentrated on a photovoltaic collector, is lost in the form of heat and the rest is converted into electricity [1, 2]. Thus, it helps increasing the electric and thermal photovoltaic panels' efficiencies. In this aspect, the higher the temperature of a solar panel is, (especially during peak-period sunshine hours) the lower its efficiency and performance will be. Moreover, the photovoltaic industry has another important issue, which is continuous need for enhancing solar panels' efficiency, which is possible by lowering their temperature [3, 4]. Subsequently, efficient cooling technologies have been introduced, which extract heat out of photovoltaic panels [5]. As yet, various studies have been conducted to analyze methods to reduce the PV panel temperature. For this purpose, efficiencies of various cooling techniques were tested [6]. Several researchers have proposed many effective and practical cooling techniques, for example, they tried air [7], water in the form of a film on the frontal surface of a PV [8],[3], water sprays on the PV surface [3], PV panel submerging in water [9], and nanofluid cooling [10],[11]. Water, which has the highest thermal conductivity among the used conventional fluids, showed a higher electrical efficiency as a coolant in a PVT system as compared to PV modules; however, such increases were restricted and confined by low thermal conductivity of normal coolants [12-15]. In addition to this, designing heat exchangers in different shapes may increase the heat transfer efficiency, which decreases temperature and improves efficiency [16]. In a study, the researchers studied a water-sprayed PV/T module both experimentally and mathematically [17]. They applied a constant collection temperature to PV/T water collectors and analyzed in addition to analyzing electrical energy and exergy values for different configurations of a collector. After applying a cooling technique, water was simultaneously supplied to a PV panel's both sides [18]. Another study was conducted to analyze the impact of panel configuration and flow rate on a PV/T's thermal performance [19]. For this purpose, they conducted their experiments on a fully-integrated thermal-electric-solar system [19]. A hybrid solar system's performance enhancement was studied when the researchers replaced water and air with a liquid metal alloy for cooling, and tested it [20]. In a study, different operating conditions were studied, including fluid inlet velocities, solar irradiations, and ambient air temperature. Thermal and electric efficiencies and the exergy of the hybrid system were evaluated when a liquid metal alloy was used. It outperformed by 11% and

12% as compared to air and water, respectively [21]. Another simulation study was conducted to compare absorber collectors' seven design configurations [21]. The simulations were conducted to test various parameters, including ambient temperature, flow rate, and solar radiation of a flat-plate thermal collector that was equipped with a single glazing sheet. They declared that the spiral flow design was the best because it had the highest thermal efficiency (50.12%) whereas the corresponding cell efficiency was 11.98%. A study [22] investigated the natural convection of flowing water through a vertical channel for reducing building-integrated photovoltaic cells' operating temperature. The modified Rayleigh number showed that the flow behavior significantly changed, which happened because of efficient mixing between the channel's slow central layer and the fast wall layer. In a study [23], the researchers investigated TRNSYS simulations for roll-bond PV/T collectors installed in many Chinese locations, including Sichuan, Western China, and Chengdu. The selected PV/T collectors had different absorber plate configurations. One of them had a conventional harp-channel configuration while the other one had a novel grid-channel arrangement. Experimental results show that the grid-channel PV/T collector had higher PV power and thermal efficiencies in comparison with the harp-channel collector, and besides, the researchers pointed out that the harp-channel PV/T collector had substantially lower water flow pressure reduction as compared to the grid-channel PV/T collector. Another experimental investigation [24] shows three new absorber designs (circular spiral, circular-spiral semi-flattened, and semi-oval serpentine) to find out their back-surface cooling and their effects on the panel performances. In a similar experiment on the serpentine design, when the results were compared, it showed that the efficiency improved by 4.32% when a circular-spiral semi-flattened design absorber was used while the fill factor was 19.80%. In an experimental investigation [25], panel cooling air was used while water was a working fluid. The experiments were conducted in Coimbatore, India in 2017. In four different cooling modes, the model's performance was estimated. Air and water cooling were applied on the collector's both surfaces. They analyzed PV water pumping system's performance using four modes of panel cooling, and compared the results to the results when there is no panel cooling, which showed performance enhancement through water cooling on the bottom surface. Other parameters, including pump efficiency, total efficiency, and photovoltaic efficiency improved by 7.7%, 1.01%, and 1.4%, respectively during the peak sunshine hours.

This study has a main objective to compare the serpentine, the PV conventional module and head and riser PV/T_S and $PV/T_{H\&R}$ modules using a square copper tube, which was cooled using distilled water at Karabuk University, which is located in Karabuk city, Turkey. It was noted that the PV panel's back surface had flow rates 0.5 and 1 L/m, which generated electric power and thermal energy from 1st to 5th August, 2019. The average of the collected data was taken for all the days and it was further used for calculations pertaining to the PV's conventional module, PV/T_S and $PV/T_{H\&R}$ modules using different parameters like the power output, surface temperature, thermal efficiency, and the total energy efficiency.

2. SYSTEM DESCRIPTION

For conducting the experiment, a test rig was developed and installed at the Karabuk University Campus from 1st to 5th August, 2019, and it was utilized for evaluating the two PV/Ts' electrical and thermal efficiencies when distilled water was used as a coolant. Besides that, hybrid PV/T and PV collectors were used and each collector consisted of a 20-watt polycrystalline silicon photovoltaic module, and two of them were PV/T serpentine, and head and riser modules (PV/T_S and $PV/T_{H\&R}$). The other one was a PV conventional module, which has been shown in Figure 1. The photovoltaic modules' specifications have been given in Table 1. The PVs are fixed to the thin copper plate's upper surface, which was 1 mm and it was welded on the back side with a serpentine, and head and riser with a square copper tube (outer diameter 10mm and inner diameter 8mm). Table 2 and Figure 2 show the actual design for serpentine, and head-and-riser heat exchangers. A thermal barrier insulation is given below. Until it formed a closed circuit, perfect contact was assured using a thermal paste between the back surface of the PV collector and the copper plate. Alterable pump was used for running the fluids (Nova company, model: RS25/4G-130) through a nanofluid storage tank, heat exchanger, and PV/T collector for cooling the warm fluid. A flow meter was used for measuring and controlling the coolant flow rates for testing at 0.5 and 1L/m (Sea company, model: YF-S201). Pico USB TC-08 thermocouple eight-channel data logger was used as a K-type thermocouple for measuring the inlet, outlet, ambient, and surface temperatures, and it was linked to a computer for collecting data. Solar radiation was measured using a pyranometer (EKO, Model MS-602, Japan) linked with a data collection board equipped with an SD card and a 4.2 inch screen to test the voltage and current for PV, PV/T, and radiation.The two systems were inclined towards South at 30° and identical conditions were assured to test them.

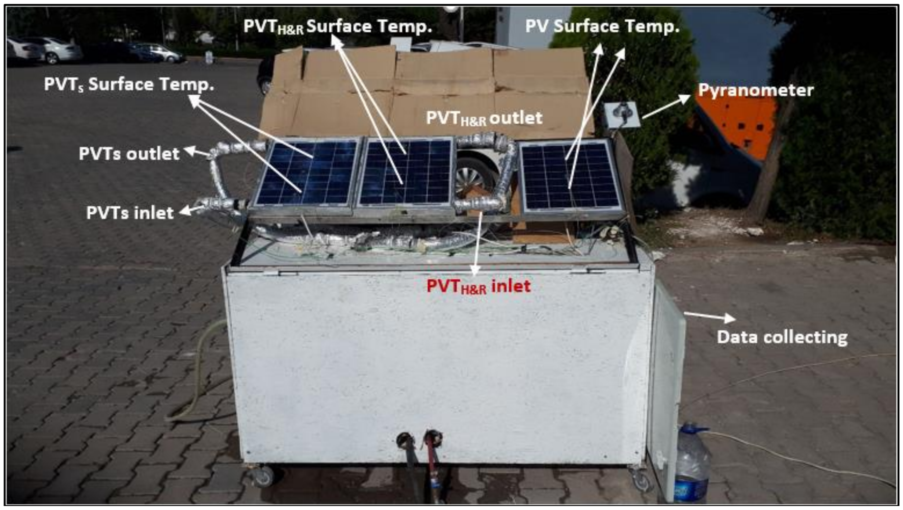


Figure 1. Schematic diagram of the experiment

Table 1. Typical PV/T panel specifications

Items	Specification
Model	LXR-020P
Brand	LEXRON
Electric Characteristics	
Open Circuit Voltage ($\mathbf{V_{oc}}$)	22.1v
Range for Power Tolerance	+5%
Maximum System Voltage	1000v
Dimensions	41.20 × 33.60 Cm
Maximum Power Current ($\mathbf{I_{mp}}$)	1.11A
Rated Maximum Power (Pmax)	20Wp
Short Circuit Current ($\mathbf{I_{sc}}$)	1.35A
Maximum Sense Fuse Rating	10.0A
Maximum Power Voltage ($\mathbf{V_{mp}}$)	18v

Table 2. Heat exchanger design specifications

Type of collector	Head, riser and Serpentine
Tube and material	Square Copper Tube
Tube dimensions	8 × 10 mm
Plate material	Copper plate
Plate dimensions	39.60 × 32.80 Cm

Figure 2. Serpentine, head and riser heat exchanger designs

3. TESTING PROCEDURE

Several experiments had been accomplished in August, and subsequently, some days were selected when there were consistent weather conditions. From 9:30 to 17:00, the mentioned experiments were conducted, during which, distilled water was used. The measurements were taken for parameters of PV/T_S and PV/$T_{H\&R}$ such as surface temperatures, solar irradiance, current and voltage generation, and coolant inlet and outlet temperatures, which were taken after every 12 seconds at 0.5 and 1 L/min controlled flow rate throughout the experiments.

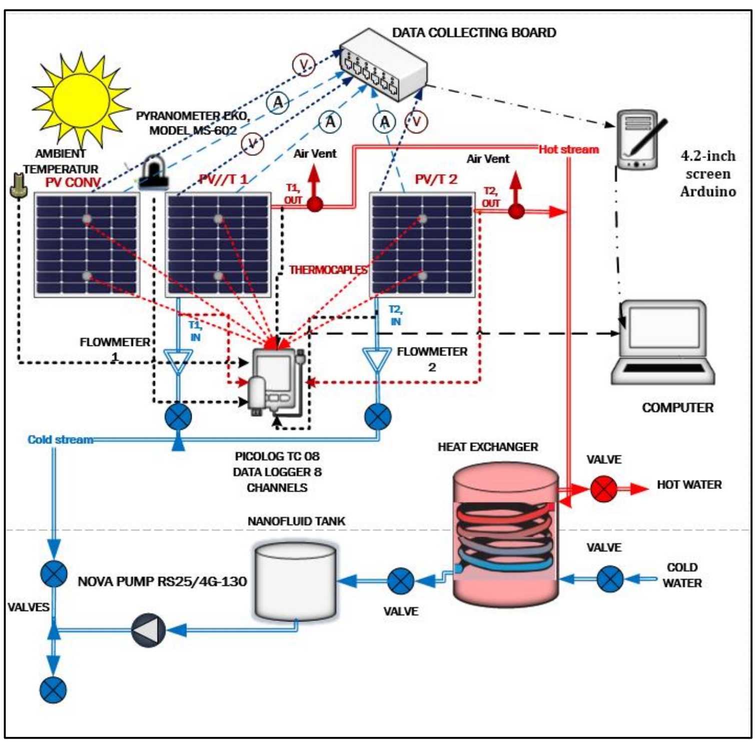


Figure 3. Schematic diagram of the experimental setup

Then, the average of the collected data was taken and further used for significant calculations. The performances of water-cooled PV/Ts and PV modules were studied and the obtained values were compared. All the experiments were conducted within the premises of Karabuk University, Turkey.

Table 3. Summary of electrical efficiency, thermal efficiency and overall energetic efficiency for selected studies of PV/T

Ref.	Type of coolant	η_{eL}(%)	η_{th}(%)	η_{ov} (%)
Alzaabi et al.[26]	Water	12.3	61.7	74
Liang et al.[27]	Water	7.2	36	43.2
Lu et al.[28]	Water	11.07	26.07	37.14
Jaaz et al.[29]	Water	11.5	81.5	93
Alous et al. [30]	Water	14.6	38.8	55.2

4. CALCULATIONS

The thermal useful power (Q_u), which is gained using a coolant in the PV/T, is given as [10, 30-38]:

$$Q_u = \dot{m}C_p(T_O - T_i) \tag{1}$$

Here, ṁ stands for the coolant's mass flow rate (kg/s), Cp shows the coolant's specific heat (kJ $kg^{-1}K^{-1}$), and the coolant's inlet and outlet temperatures are shown by T_i and T_o.

The output power is obtained from PV and PV/T model based on Eq. 2 [10, 30-38]:

$$P = I \times V \tag{2}$$

Here, I stands for output current (A) and V represents the output voltage. From solar radiation, the PV/T's thermal efficiency has been extracted. Both efficiencies, namely thermal (η_{th}) and electrical (η_{el}) have been given in Eq. 3 [10, 30-38]:

$$\eta_{th} = \frac{Q_u}{I_R \times A_{th}} \tag{3}$$

The electrical efficiency is expressed through Eq. 4 [10, 30-38]:

$$\eta_{el} = \frac{P}{I_R \times A_{PV}} \tag{4}$$

In the equations mentioned above, A_{PV} shows the area of PV cells, A_{th} shows the area of the PV/T collector (m^2), and I_R stands for solar radiation on the surfaces of PV and PV/T (Wm^{-2}). For obtaining the PV/T collector's energy efficiency (η_{ov}), both thermal and electrical efficiencies are as follows [34-36]:

$$\eta_{ov} = \eta_{th} + r.\eta_{el} \tag{5}$$

Here r = $r = A_{pv}/A_{th}$ represents the packing factor.

Eq. 6 shows the electrical efficiency enhancement $\Delta_{eL,}$ [10, 30, 31, 37]

$$\Delta_{eL,} = \frac{\eta_{pvt,el} - \eta_{pv,el}}{\eta_{pv,el}} \times 100 \tag{6}$$

5. RESULTS AND DISCUSSION

Many experiments were conducted on the cooling operation of PV/T modules. Measurements were noted after every 12 seconds Table 4 from 09:30 to 17:00 at 0.5 and 1 L/m flow rates for two time periods: Peak period (11:15 to 15:15) and all-day period (09:30 to 17:00) for the under investigation coolant. First, on 1st August 2019, an experiment was performed on distilled water at 1 L/m flow rate in stable weather conditions and the second using distilled water on 5th August 2019 at 0.5 L/m flow rate. Due to unstable weather conditions on other days, several experiments and their results were ignored.

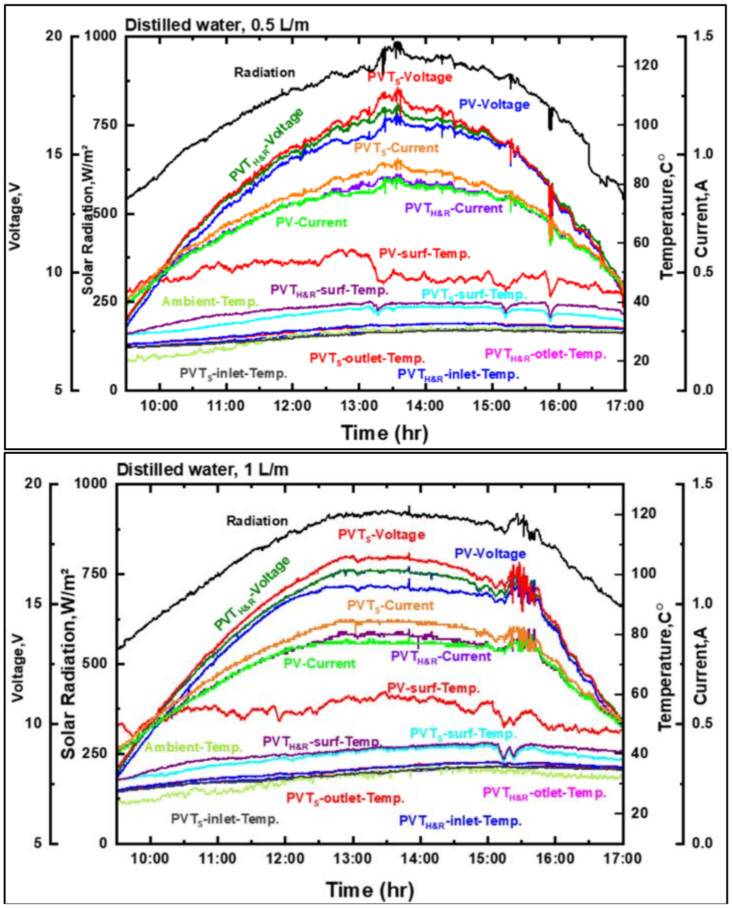


Figure 4. Parameters measured daily after every 12 seconds

5.1 Solar Irradiance and Ambient Temperature

The direction of the experimental module was 30° [39] towards South for appropriately getting solar radiation. Figure 5 shows that at around 15:15, the highest ambient temperature was noted, and then, it gradually decreased to 30°C until 17:00 when the experiments ended. At 13:45, the solar radiation became maximum almost 908W/m² that slowly declined to 530W/m² by 17:00. All data were taken from the experiments and presented in Table 4.

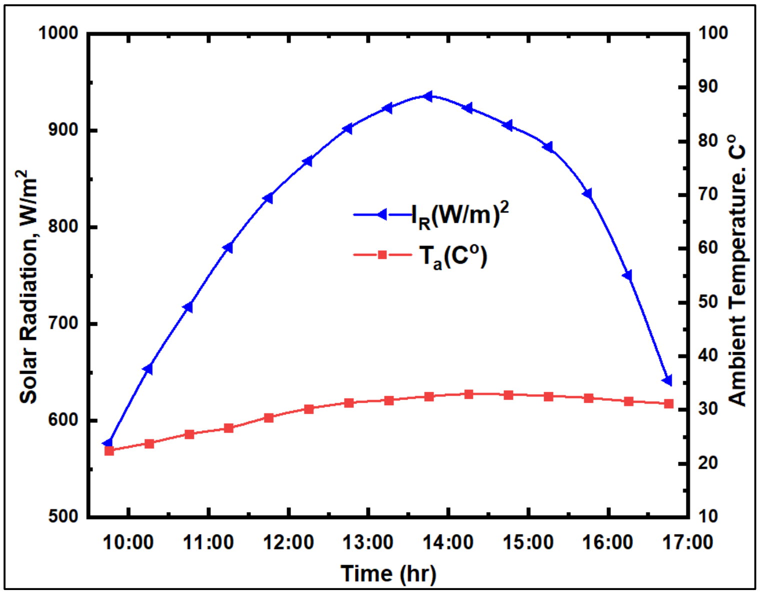


Figure 5. Daily average ambient temperature and solar radiation intensity

5.2 Surface Temperature Measurement

In Figure 6, the PV/T_S, PV/$T_{H\&R}$ and PV collectors' surface temperatures are given. They were noted at the time of cooling with distilled water from 09:30 to 17:00. The surface temperature of PV/T_S and PV/$T_{H\&R}$ collectors significantly decreased as compared to the simple PV collector. The first experiment was conducted on 1 August 2019 from 09:30 to 17:00 and cooling was done at 1 L/m flow rate when both ambient temperature and solar radiation were high and there was a longer daylight time. Moreover, the surface temperatures for the PV/T_S, PV/$T_{H\&R}$ and PV conventional in the all-day period at 1 L/m flow rate were 38.8°C, 40.1°C and 53°C, respectively, whereas the surface temperatures for the PV/T_S, PV/$T_{H\&R}$ and PV conventional in the peak period at 1 L/m flow rate were 40.7°C, 41.6°C and 56°C, respectively. It was noticed that the radiation reduced after the mid-day that decreased the PV surface temperature but it did not affect the outlet, inlet, and PV/T collectors' surface temperatures, which gradually reduced when the test finished (Figure 6a).

On 5 August 2019, another experiment was conducted (09:30 to 17:00) at 0.5 L/m flow rate. As Figure 6b shows, most part of the day, the weather was steady. The PV/T_S, PV/$T_{H\&R}$ and PV conventional showed gradual surface temperature rise from 27-38°C and 39.5-45.8°C between 09:30 and 14:45, and they further declined until 17:00. Moreover, the surface temperatures for the PV/T_S, PV/$T_{H\&R}$ and PV conventional for the whole day at 0.5 L/m flow rate were 35°C, 37.5°C, and 49.4°C, respectively while the surface temperatures for the PV/T_S, PV/$T_{H\&R}$ and PV conventional in the peak period at 1 L/m flow rate were 37°C, 39°C and 50.6°C, respectively. As a result, for all the experiments, when the solar radiation increased, PV, PV/T_S and PV/$T_{H\&R}$ surface temperatures and the coolant fluid temperature increased as well. The maximum surface temperature values for the PV, PV/T_S and PV/$T_{H\&R}$ collectors with distilled water at flow rates 0.5 and 1 L/m were 14.40°C and 14°C, which indicate the different between PV surface temperature and PV/T surface temperature DeltaT for PVT/s and PVT/$_{H\&R.}$

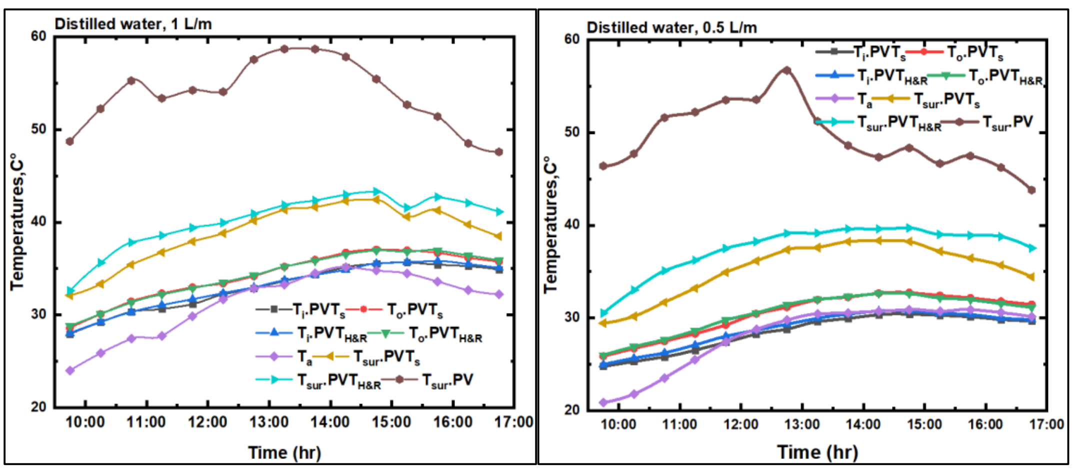


Figure 6. Daily average surface temperature variations in PV, PV/T_S, and PV/$T_{H\&R}$

Figure 7 shows cooling distribution for PV/T_S, PV/$T_{H\&R}$ and PV collectors, which revealed that the PV/T_S and PV/$T_{H\&R}$ are covered nearly 90% by cooling fluid from the surface area of the collectors whereas PV conventional collector was hotter than the other collectors.

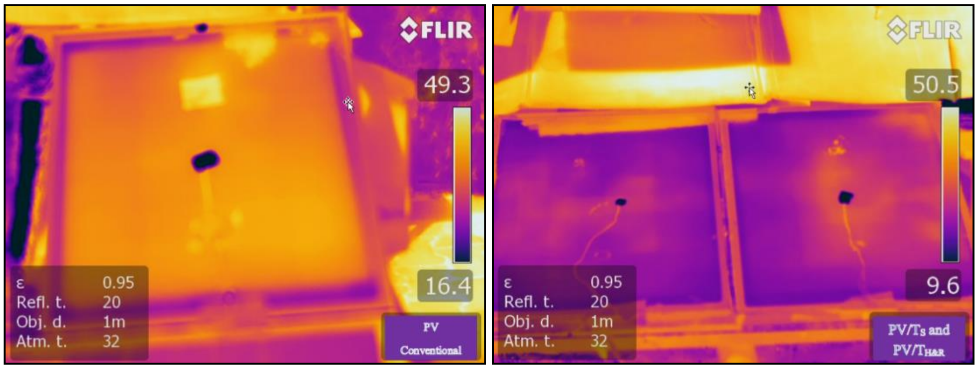


Figure 7. Temperature distribution of PV/T$_S$, PV/T$_{H\&R}$, and PV collectors

5.3 Electrical Power And Efficiency

First the surface temperature was measured and its impact was evaluated on PV/T and PV surfaces to understand how a coolant should be used for reducing the temperature and improving PV/T collectors' electric and energy performances. It was found that both electrical energy and the power generation through PV and PV/T$_S$ collectors followed solar radiation, and power generation maximized whenever the solar radiation was maximum. Table 4 and Table 5 present PV and PV/T surface temperatures, solar radiations, electrical efficiencies, and enhancements in electrical efficiency for both the time periods (all-day and peak periods). Electrical power, thermal efficiency, and electrical efficiency were averaged after every 30 minutes. They are illustrated for every half hour and used for further calculations.

Table 4. Average weather conditions, power enhancement, and cell temperature during the experiment period (9:30 - 17:00) at flow rates 0.5 and 1.0 L/m

Type of Coolant	F.R L/m	I_R W/m²	T_{amb} (C°)	$T_{S,PV}$ (C°)	$T_{S,PVT}$ (C°)	$T_{S,PVT_{H\&R}}$ (C°)	$\eta_{PV,eL}$ (%)	$\eta_{S,eL}$ (%)	$\eta_{H\&R,eL}$ (%)	$\Delta_{eL,S}$ (%)	$\Delta_{eL,H\&R}$ (%)
Water	0.5	809	28.2	49.6	35.0	37.5	8.6	9.6	9.1	8.8	3.5
Water	1.0	813	31.0	53	38.8	40.1	9.0	10.0	9.3	11.6	4.0

Table 5. Average cell temperature, electrical enhancement, and weather conditions during the peak period (11:15 – 15:15) at flow rates 0.5 and 1.0 L/m

Type of Coolant	F.R L/m	I_R W/m²	T_{amb} (C°)	$T_{S,PV}$ (C°)	$T_{S,PVT}$ (C°)	$T_{S,PVT_{H\&R}}$ (C°)	$\eta_{PV,eL}$ (%)	$\eta_{S,eL}$ (%)	$\eta_{H\&R,eL}$ (%)	$\Delta_{eL,S}$ (%)	$\Delta_{eL,H\&R}$ (%)
Water	0.5	895	30.0	50.6	37.3	39.0	10.3	11.3	10.6	10.0	3.8
Water	1.0	892	33.0	56.0	40.7	41.6	10.4	11.9	11.0	14.0	5.0

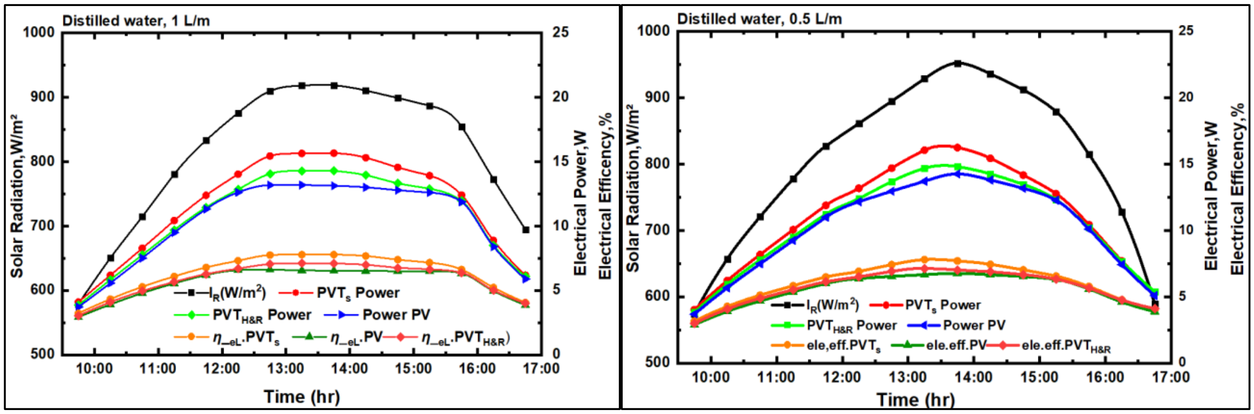


Figure 8. Power production and electric efficiencies of PV, PV/T$_S$, and PV/T$_{H\&R}$ collectors

Figure 8 shows electrical power increase when solar intensity is increased, and it was noted that during the experimental periods, the daily average solar radiation remained 809 and 813W/m^2 for all-day period and 895 and 892 W/m^2 for the peak period, respectively. The experimental data includes radiation, electrical efficiency enhancement, and ambient temperature, which were averaged and divided by two for all-day and peak periods, and then, PV/T$_S$, PV/T$_{H\&R}$ and PV conventional were compared. Different types of heat exchangers PV/T$_S$, PV/T$_{H\&R}$ showed significant increase in the output power at 9.6%, 9.1% at 0.5 L/m flow rate and 10%, 9.3% at 1 L/m flow rate as compared to PV conventional, which were 8.6% at 0.5 L/m and 9.0% at 1 L/m for all-day period. During peak period, they were 11.3%, 10.6% at 0.5 L/m flow rate and 11.9% at 1 L/m flow rate, and 11% as compared to PV conventional 10.3%, 10.4% during peak period.

5.4 Improvement In Electrical Efficiency

It has been mentioned before that surface temperatures of the PV/Ts, PV/T$_{H\&R}$ and PV increased when solar radiation increase was noticed from the beginning of the experiments till the end but it reduced electrical efficiencies of PV/T$_S$ and PV/T$_{H\&R}$. Thus, the coolant is used for gradual heat extraction, which improves electrical efficiency. Figure 9 shows that the PV/T$_S$ at both 0.5 and 1 L/m flow rates have undergone the highest electrical efficiency enhancement than the PV/T$_{H\&R}$. This indicates that the PV/T$_S$ design is better than PV/T$_{H\&R}$ that results in faster PV/T heat disposal than PV/T$_{H\&R}$ Eq. (6). Table 4 and Table 5 show the daily average electricity enhancements for both peak and all-day periods.

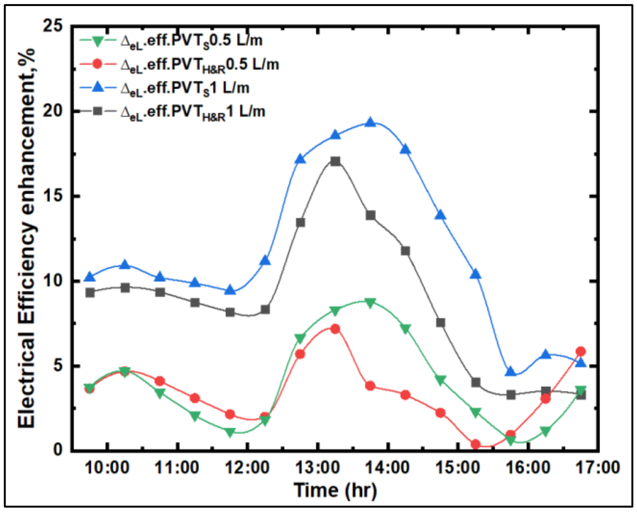


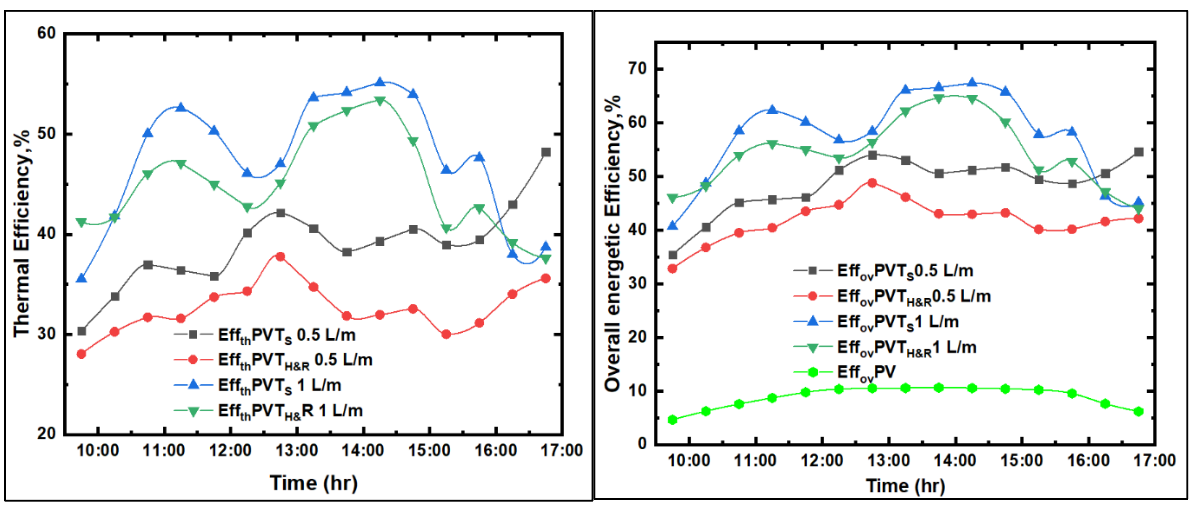
Figure 9. Average daily variations in electrical efficiency enhancement

5.5 Thermal and Overall Energy Efficiency

In this study, the overall energy efficiency was computed applying Eq. (5), as Figure 10b shows. Since the collector area covered all the photovoltaic cells and there is a perfect contact between the collector and the PV cell with an assumption, the packing factor is equal to one. The results indicate that distilled water at 1 L/m and 0.5 L/m flow rates for PV/T_S showed the highest thermal efficiency and the overall energy efficiency as compared to distilled water at 1 L/m and 0.5 L/m flow rates for PV/$T_{H\&R}$. Moreover, the overall energy efficiency increased during the day when the thermal efficiency increased. In this study, the thermal efficiency is more as compared to the thermal efficiency mentioned by Alous et al. [40] and the values mentioned by Sardarabadi et al. [41]. They used PV/T design with circular tube at 0.5L/m flow rate. Consequently, the average daily overall energy efficiencies for all-day periods for distilled water PV/T_S were 48.6% and 59.4%, respectively, and the daily overall energetic efficiencies for the peak periods for distilled water PV/T_S were 50.8% and 64.3%, respectively, at flow rates 0.5 and 1L/m. The average daily overall energy efficiency values for the all-day periods for distilled water PV/$T_{H\&R}$ were 41.7% and 54.7%, respectively, and the daily overall energy efficiency for the peak periods for distilled water PV/$T_{H\&R}$ were 43.9% and 59.0%, respectively, at 0.5 and 1 L/m flow rates. The reference PV system's average overall efficiency with no cooling was almost 9% for the all-day period and 10.1% for the peak period. This confirms that for improving the overall PV energy efficiency, thermal cooling units should be used. On the other hand, as Figure 10a shows, the PV/Ts' average daily thermal efficiencies during the all-day periods obtained by Eq. (3) were 39% and 49.4%, and for the peak periods, they were 39.5% and 52.4%. The average daily thermal efficiencies for the all-day periods for $PV/T_{H\&R}$ were 32.6% and 42.4%. For the peak periods, the efficiencies were 33.3% and 48.0% in case of distilled water at flow rates 0.5 and 1L/m, respectively. The results show that thermal efficiency values obtained in this study are more as compared to reference values mentioned in a previous study [40], which were 38.8% for all-day periods and 38.9% for the peak periods when distilled water was used as a coolant. Table 6 and Table 7 summarize the total energy efficiency and average daily thermal efficiency for PVT. The experimental results depend on factors like type of cooling, solar radiation, and ambient temperature.

Table 6. Average thermal and overall energy efficiencies for PV/T_S with coolant at 0.5 and 1 L/m flow rates

Type of Coolant	F.R L/m	(9:30 – 17:00) period		(11:15 – 15:15) period	
		η_{th} (%)	η_{ov} (%)	η_{th} (%)	η_{ov} (%)
Distilled water	0.5	39.0	48.6	39.5	50.8
Distilled water	1.0	49.4	59.4	52.4	64.3



a) b)

Figure 10. Average daily variations in thermal efficiencies and the overall energy efficiencies of PV, PV/T_S and $PV/T_{H\&R}$

Table 7. Average thermal efficiency and the overall energy efficiency for $PVT_{H\&R}$ with coolant at 0.5 and 1 L/m flow rates

Type of Coolant	F.R (L/m)	(9:30 – 17:00) period		(11:15 – 15:15) period	
		η_{th} (%)	η_{ov} (%)	η_{th} (%)	η_{ov} (%)
Distilled water	0.5	32.6	41.7	33.3	43.9
Distilled water	1.0	45.4	54.7	48.0	59.0

6. CONCLUSIONS

This study demonstrates different effects of using distilled water as a coolant for different heat exchanger configurations with a square-shaped tube. The experimental investigation was carried out for evaluating a PV/T system's thermal and electrical efficiencies. As mentioned before, distilled water was used as a coolant and 0.5 and 1 L/m were selected as flow rates to carry out the experiments. The PV/Ts and $PV/T_{H\&R}$ systems were also compared with a conventional PV system at almost 30° tilt angle. The results of this study showed that:

1. Using PV/T_S and $PV/T_{H\&R}$ model reduce the average surface temperature by 14.2% and 11.9% at 0.5L/m flow rate, and 14.5 % and 12.9% at 1L/m flow rate when the average daily solar radiation is 803 and 813W/m^2 respectively.
2. Electrical efficiency of the utilized PV/T_S and $PV/T_{H\&R}$ models increased by 9.6%, 9.1% and 8.8% for PV conventional at 0.5L/m flow rate respectively, whereas it was 10%, 9.3% and 9% at 1 L/m flow rate for PV/T_S, $PV/T_{H\&R}$ and PV respectively.
3. The electrical efficiency enhancement showed that PV/T_S is more effective than $PV/T_{H\&R}$ at both the flow rates: 0.5 and 1 L/m.
4. The PV/Ts has 39.0% and 49.4% thermal efficiency values, which are higher than the thermal efficiency values for $PV/T_{H\&R,}$ 32.6% and 45.5% at 0.5 and 1 L/m flow rates, respectively.
5. The overall energy efficiency of PV/T_S increased by 48.6% and 59.4% and it increased for $PV/T_{H\&R}$ by 41.7% and 54.7% at 0.5 and 1.0 L/m flow rates, respectively.
6. This study proved that the serpentine design with a square-shaped tube has the highest thermal efficiency as compared to the circular-shaped tube.

NOMENCLATURE

$\mathbf{I_R}$	Solar radiation [Wm^{-2}]	T_{amb}	Ambient temperature [°C]
$\mathbf{\Delta_{S,PV}}$	PV surface temperature [°C]	PV/T_S	Serpentine collector
$\Delta \mathbf{Ts_s}$	Serpentine surface temperature [°C]	$PV/T_{H\&R}$	Head & riser collector
$\Delta \mathbf{Ts_{H\&R}}$	Head & riser surface temperature [°C]	PV	Conventional collector
$\eta_{\mathbf{PV,eL}}$	Electrical efficiency PV [%]	Cp	Specific heat [$kJ\ kg^{-1}K^{-1}$]
$\eta_{\mathbf{S,eL}}$	PV/T_S electrical efficiency [%]	T_i	Inlet temperature [°C].
$\eta_{\mathbf{H\&R,eL}}$	Head & riser electrical efficiency [%].	T_o	Outlet temperature [°C].
Δ_{el}.eff. $\mathbf{PV/T_S}$	Serpentine electrical enhancement [%]	Ta	Ambient temperature [°C].
Δ_{el}.eff.$PV/T_{H\&R}$	Head & riser electrical enhancement [%]	P	Power [w].
$\mathbf{Q_u}$	Thermal useful power [%]	F.R	Flow rate [m/s]
$\boldsymbol{\eta_{th}}$	Thermal efficiency [%]	A_{pv}	PV area [m^2]
$\boldsymbol{\eta_{ov}}$	Overall energy efficiency [%]	A_{th}	PV/T area [m^2]

Declaration of Ethical Standards

The authors of the paper declare that nothing, which is necessary for achieving the paper, requires ethical committee and/or legal-special permissions.

Contribution of the Authors

Omran Alshikhi: Methodology, Investigation, Writing – Original Draft, Visualization.

Muhammet Kayfeci: Supervision, Project administration.

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