The Effect of Adding Paraffin Wax to PVT Collector on Its Efficiency: A Practical Study

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Abstract- The efficiency of a PV plate is not more than 20% depending on its type, because more than 80% of the solar radiation falling on the PV panel is not converted into useful energy. In order to increase the PV efficiency, several studies have been conducted to convert it to a hybrid PVT system by adding a heat exchanger to its back surface. The present study involves a comparison of the thermal performance between a conventional PVT and a modified PVT collector containing a layer of paraffin wax on the heat exchanger. An experimental platform was established in the Iraqi city of Kirkuk (latitude 35.467 north and longitude 44.38 east) and experiments were conducted in February 2020 in two parts. The first part is an experiment without water circulation and the second part involves water circulation at a constant flow rate of 1 LPM. In the first part, the experiment result showed that paraffin wax caused a decrease in the electrical efficiency of the PV panel by 5.3% due to the temperature rise of the surface of the photovoltaic plate. On the other hand, the result of the second part of this study showed that the use of paraffin wax has an advantage in improving the total efficiency of the hybrid MPVT system, as it maintains its thermal efficiency of over 60% in periods after 12:00 p.m. as a result of storing thermal energy in the wax layer. Also, two mathematical relations were obtained that express the instantaneous efficiency for each collector.

Keywords PV/T collectors; solar hybrid system; overall efficiency; collector efficiency;

Nomenclature

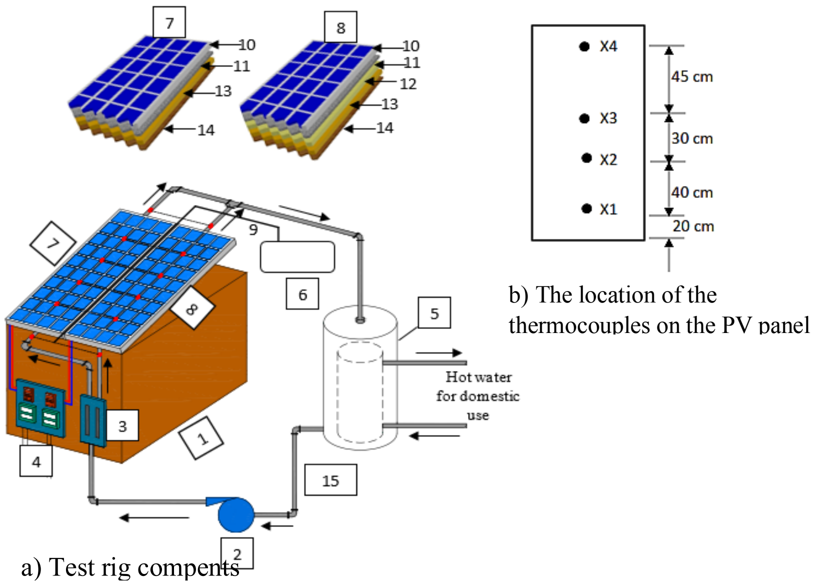
A	Area of PV panel (m^2)	ρ	Density of the water (kg/m^3)
C_P	Specific heat of water (J/kg.°C)	τ	Transmissivity
F_R	Heat removal factor	***Subscript***	
I	Current (A)	*a*	Ambient
G	Incident solar radiation intensity (W/m^2)	b	Bulk
$\dot{m}$	Water mass flow rate (kg/s)	c	Cell
Q	Heat transfer rate (W)	el	Electric
T	Temperature (°C)	i	Inlet
V	Electrical potential difference (DCV)	o	Outlet
$\dot{V}$	Volumetric flow rate (m^3/s)	PVT	Total
U_L	Overall heat loss coefficient ($W/m^2.°C$)	ref	Standard condition
Greek symbols		th	Thermal
α	Absorptivity	u	Useful
η	Efficiency		

1. Introduction

The rapid increase in global energy consumption is directly related to a rise in global population and industrial activity, contributing to increased environmental pollution, carbon dioxide emissions, and global warming [1]. Photovoltaic (PV) design to convert solar radiation into electrical power with a maximum efficiency that ranges from10 to 20% depends on the PV panel type; more than 80% of solar radiation that falls on the PV panel doesn’t convert to useful electrical energy[2] . For this reason, the researchers are interested in regaining the loss heat by using integrated photovoltaic thermal (PVT) systems, as these types of hybrid (PVT) systems can simultaneously generate heat and electrical energy. The first studies have been conducted and published in the past 40 years[3] by Wolf (1976) [4], Florschuetz (1979) [5], and Raghuraman (1981) [6], using a hybrid PVT system based on water and air as a coolant. The authors found that the system becomes more efficient when it uses water as a coolant. After that, many theoretical and experimental studies were conducted on this system. Ibrahim et al. (2009) [7] have developed two hybrid PVT air and water collectors and conducted experimental studies. examining the effect of mass flow rates on the electrical and thermal efficiencies of the hybrid PV/T systems. Joshi et al. (2009) [8] studied the thermal performance of two different PVT air collector models (glass-to-floor and glass-to-glass). The authors found that the glass-to-glass PVT collector has higher efficiency than any other type. Bai et al.(2012) [9] have done an experimental study on a combined PVT system-assisted heat pump for a sports center. The authors got an energy-saving factor of 67% compared to the conventional system. Bayindir et al. (2012)[10] Investigated experimentally and theoretically, optimizing PV panels' operation based on the monthly linear load curve. The simulations included the PV surface temperature, the plate deflection angle, and the electrical load effect on the output power. Jazayeri et al.(2013) [11] analyzed the effect of experimentally different values of the solar irradiance intensity and electrical connections type on the PV panels' performance. Aste et al. (2013) [12] have presented a mathematical model to estimate an unglazed hybrid PVT's electrical and thermal production with water as heat transfer fluid. The present study shows a detailed performance prediction model applicable to uncovered PVT collectors and the experimental validation carried out on a commercial module. Hui et al.(2014) [13] The preservation capacity of the PV/T hybrid collector was studied by TRNSYS software. The operating parameters and the ratio of tube distance to the tube diameter were investigated. TRNSYS results showed that a decrease in tube distance ratio to tube diameter leads to enhanced electrical and thermal efficiency. Mohammed et al. (2014)[14] presented a comparative study between the PV model and PVT hybrid collector. In this study, electrical and thermal energy were analyzed. The results of the analysis showed that PVT increases electrical efficiency by 4.6% and absorbs heat energy from the photovoltaic plate to heat water with an efficiency of 23%. Haddad et al. (2015) [15] experimentally examined the electrical and thermal efficiencies of a PVT collector. This study aimed to cool the PV panel and use hot water for domestic use. They compared their results with the performance of these separate PV panel and water heating collector. Tiwari et al. (2016)[16] have analyzed PV panel energy integrated with a greenhouse for biogas heating. They studied some parameters, such as ambient temperature and solar intensity, measured in the experiment location. The result of the analysis showed that the average overall efficiency throughout the day was about 69%. Mosalam (2018) [17] the design and operation of photovoltaic panels has been studied experimentally. The aim of this study was to include the effect of panel orientation and tilt angle on their power generation and were tested for different inverter-maximum power point tracking (MPPT). Arefin M. A.(2019) [18] presented a numerical and experimental study to evaluate the thermal efficiency of the water-cooled PV panel. Abdullah et al. (2020) [19] presented a theoretical and experimental study on the thermal performance of the water hybrid PVT with a different water flow rate ranging from 2 to 6 LPM, and the solar radiation ranged from 500 to 1000 W/m^2. They found that the overall efficiency increased when the mass flow rate increased. Kader et al. (2019) [20] introduced a new dual PVT system design, involving air and water circulation with modifications in the air channel is presented. Modifications included: first, placing a thin metal sheet inside the air channel, and second, using a black polygonal surface below the air channel. The aim is to examine the heat dissipated from changing rib surfaces (trapezoid, saw teeth forward, saw teeth backward) ribbed surfaces and flat surface. Four experiments were conducted during the months from February to June. The comparative results showed that the trapezoid was the best. Its average efficiency was 64% while the flat surface gave the lowest efficiency estimated at 58%. Elsir et al. (2019) [21]have analyzed the cost optimization of the PV panels based on the declination angle and power generation. The present studied solar storage energy system on the distributed generators unit. Ghasemzadeh et al.(2020)[22] studied the effect of temperature challenges on PV efficiency. The current study was conducted on several parameters, such as the variable density method, different from the monolayer bismuth, including the structural, optical, and electronic properties under various stresses biaxial in a homogeneous manner the amplified plane waves of the linear voltage system. Diwania et al. (2020) [23] reported a literature review on the design of PVT, its applications, and its features. Gorba and Yesilata (2019) [24] presented an in-depth review of the many previous studies on improving the performance of the hybrid PVT systems. Many of these have included comparative studies between experimental and theoretical. Abd Allah (2018) [25] has provided an in-depth look at the erosion of photovoltaic panels resulting from environmental pollution and ways to control it. A few studies performed on the hybrid PVT system based on the nanofluids. They suggested conducting experimental studies under actual weather conditions by reviewing these studies without neglecting the impacts of nanofluid's mass flowrate variations. This study aims to examine the effect of paraffin wax addition on the performance of a conventional hybrid PVT system, by investigation the surface temperature distribution on the PV panels and overall efficiency of the modified hybrid photovoltaic thermal (MPVT) system and traditional photovoltaic thermal (TPVT) system, in two cases, with and without water circulation. The result of the hybrid PVT collector, which contains paraffin wax in each case, is compared with the conventional PVT collector to assess the improvement ratio obtained with paraffin wax. Adding paraffin wax to PVT collector increases thermal efficiency if the water is used as a coolant system. Finding a correlation equation to predict hybrid solar collector designs .

2. Experimental setup

In the current study, a test rig has been setup in Kirkuk, Iraq (35.467 N latitude and 44.38 E longitude). The rig which contains two hybrid PVT collectors, similar in size and specifications. One of them has a layer of paraffin wax of a 3 cm added to it. Fig.1 shows a schematic diagram of the test rig and Table 1 enlists the technical specifications of its components. The traditional PVT collector is named (TPVT) contains a monochromatic PV panel of 150 W and 13% reference efficiency. A plate heat exchanger and a glass wool layer are inserted into the backside of the PV panel and then covered with a wooden layer. The other collector, named MPVT is similar to TPVT, except for a waxy layer inserted between the heat exchanger and the glass wool. Both collectors are connected to an external heat exchanger to heat watar for domestic use through the piping system, which contains a centrifugal pump and two water flow control devices. Two data loggers have been used to record experimental data automatically; the first one is a temperature data logger, type (Applent AT4516), used to record the temperature at 16 locations in both collectors by K type thermocouple, and the second is a wireless weather station type (HP2000), used for weather condition recording. Both recording devices are set on 20 min for recording data. Two types of experiments were carried out on this test rig in February, 2020. In the first case, the experiment was carried out without water circulation in the first half of February with the aim of examining the effect of the paraffin wax on the electrical efficiency of the PV panel only, when it works as a power generator. The second experiment was started in the second half of February, using circulating water in both collectors at a flow rate of 1 LPM.



a) Test rig compents

b) The location of the thermocouples on the PV panel

Fig. 1. Schematic diagram of the test rig used in the

Table 1. Specifications of the test rig components

Part No.	Part Name	Specification
1	Base	MDF Wood panel (120×165×60) cm
2	Centrifugal pump	4 LPM, 240 ACV
3	Rotameter	0-4 LPM
4	Electric control board	Solar charge controller and inverter (12 DCV to 240 ACV)
5	Heat exchanger	External cylinder 60 L and internal cylinder 40 L
6	Temperature data logger	Type Applent AT4516, 16 channel
7	TPVT	Traditional photovoltaic thermal collector
8	MPVT	Modified photovoltaic thermal collector
9	Extension wire	Thermocouple type K (16 set)
10	Photovoltaic panel	Monocrystalline type, 150 W
11	Heat exchanger	Aluminum plate heat exchanger (145×50×0.2) cm
12	Paraffin wax	Paraffin wax layer (9.5 kg weight)
13	Insulation layer	Glass wool 5 cm thick
14	Cover	Wood fiber layer 0.8 cm thick
15	Piping system	PVC pipe 0.25-inch diameter.

3. Determination of hybrid PVT system efficiency

The performance of the collectors can be described by a combination of effective expression. It is comprised of thermal efficiency(η_{th}) and electrical efficiency(η_{el}). The total efficiencies, which is known as the combined PVT efficiency (η_{PVT}) is used to evaluate the overall thermal performance of the PVT system, and can be expressed as[17]:

$$\eta_{PVT} = \eta_{th} + \eta_{el} \tag{1}$$

The thermal efficiency of the PVT collector is the ratio of the useful thermal energy to the total incident radiation energy, given by[26]:

$$\eta_{th} = {Q_u}/{(A \times G)} \tag{2}$$

where Q_u can be calculated as [27]

$$Q_u = \dot{m} C_p (T_o - T_i) \tag{3}$$

and

$$\dot{m} = \rho \dot{V} \tag{4}$$

whereas the physical properties of water such as ρ and C_p are estimated at the bulk temperature T_b, given by:

$$T_b = {(T_o + T_i)}/{2} \tag{5}$$

The electrical efficiency of the PV panel is the ratio of power generation to the energy of the incident solar radiation, and it is expressed as follows:

$$\eta_{el} = V \times I/(A \times G) \tag{6}$$

It is known that the efficiency of a PV panel depends on the temperature of the cell, and it can be calculated based on Refs, which were presented as[19][28]

$$\eta_{el} = \eta_{ref} - 0.0045(T_c - T_{ref}) \tag{7}$$

The instantaneous efficiency of the collector is calculated under steady-state conditions and is based on the ASHRAE standard 93 (1983) because it is needed for designing purposes and commercial values of the collectors. The efficiency is calculated as follows [29] :

$$\eta_{th} = F_R \alpha \tau - F_R U_L (T_o - T_i)/G \tag{8}$$

4. Experimental uncertainty analysis

Experimental uncertainty was calculated based on Gaussian distribution law. Uncertainty (R) can be calculated as a function of the independent variables x_1, x_2, ..., x_n and w_1, w_2, ..., w_n with the uncertainties in the independent variables. Thus, the uncertainty in the result (w_n) can be computed as follows [30][31]**:**

$$w_R = [(\partial R/\partial x_1 \times w_1)^2 + (\partial R/\partial x_1 \times w_2)^2 + \cdots + (\partial R/\partial x_1 \times w_n)^2]^{1/2} \tag{9}$$

The uncertainty of the measuring instruments was calculated on the basis of the references. [30] and [31]. The results are shown in Table 2. The maximum uncertainty of total efficiency is ±2.3%, which is determined from Eq. 9.

Table 2. Uncertainty of the measuring devices used in the current study.

Device name	Resolution	Accuracy	Uncertainty
Voltmeter	0.01 V	±(0.8+5) V	±0.1049 V
Ammeter	0.01 A	±(0.2+5) A	±0.0379 A
Rotameter	-	±0.04 LPM	±0.065LPM
Temperature data logger	0.5ºC	±0.01ºC	±0.291ºC
Solar meter	0.2 W/m^2	±0.15 W/m^2	± 0.325
Tap measure	0.0254 mm	±0.127 mm	±0.526 mm

5. Results and discussion

Results obtained from two different working conditions were analysed to determine the effect of adding paraffin wax on the temperature distribution behavior on the PV panel surface and total efficiency for both thermal systems. The best weather conditions data were used for analyzing the results in both working condition cases. The weather of February 5 was selected for the first experiment, while the weather of February 27 was used for the second experiment. Also, the instantaneous efficiency of the collectors was evaluated based on the ASHRAE standard 93(1983).

5.1 When PVT collectors operate without circulating water.

a. Temperature distribution on the PV panel surface.

The weather for February 5 was chosen in an analysis of the performance of both colleges because the weather on that day was the best for the period from February 1 to 14. Fig. 2 shows the ambient temperature and solar radiation intensity versus time on February 5. Fig.2 shows the weather on 2/5/2020, and we notice that the ambient temperature dropped rapidly after 9:00 a.m., and that the major fluctuations in it occur during the hours of 11:00 a.m. until 2:00 p.m., where it was fluctuated from (-8.8 to 14.7ºC). Solar radiation did not affect by changes in the ambient temperature other than at 10:20 a.m. for a short time, where the maximum solar radiation intensity was at 340 W/m^2. A clear effect of paraffin wax on the temperature distribution on the PV panel was observed from Figs 3 and 4. In MPVT collector the difference in surface temperature distribution was much higher than TPVT collector due to paraffin can store energy from PV panel and to change its state from the solid-state to the liquid phase when its temperature reaches the melting temperature of about 45ºC. Its temperature rises when it is completely transformed into a liquid state. It was also observed that the change was less in the temperature distribution on the PV panel of the TPVT collector compared to the MPVT collector. The highest level of temperature distribution occurred at 2:00 p.m. in both collectors, but with different value and location, in a TPVT collector, the highest temperature was reached at 53 ° C at location X3, while in the MPVT, the highest temperature was 59 ° C at a distance of 7.5 cm from the location X2. It indicates that the concentration of paraffin wax increased at this location through the melting process.

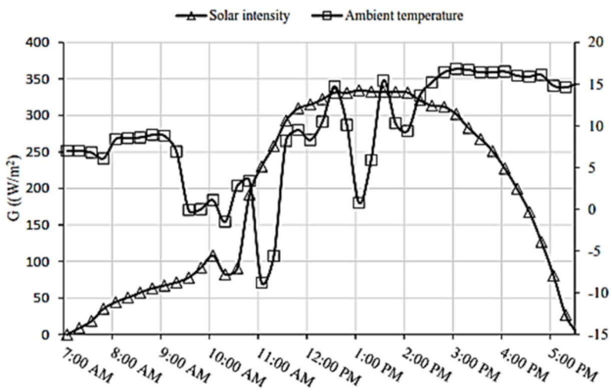


Fig.2. Weather details for the experiment conducted on February 5, 2020.

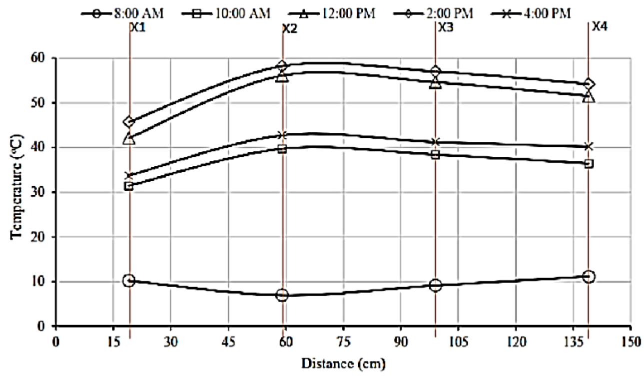


Fig.3. Temperature distribution on the PV panel for the TPVT collector on February 5, 2020

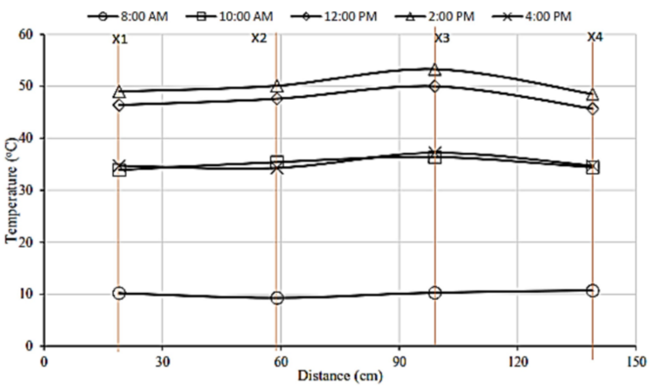


Fig. 4. Temperature distribution on the PV panel for the MPVT collector on February 5, 2020

b. *Electrical efficiency*

The aim of this part of the experiment was to examine the effect of paraffin wax on the efficiency of the PV panel. The results of the experiment show that the use of wax had a negative effect on efficiency. This is due to the high surface temperature of the PV panel, as shown in Fig. 5. Note that the electrical efficiency increased against time until 1:00 p.m. This indicates the apparent effect of rising PV surface temperature on the efficiency. What is also observed is that the efficiency of the TPVT collector was higher than that of the MPVT, with the former ranging between 5.8 and 12.6% while the letter went between 5.4 and 11.6% for MPVT collector, that is an average loss of 5.3%.

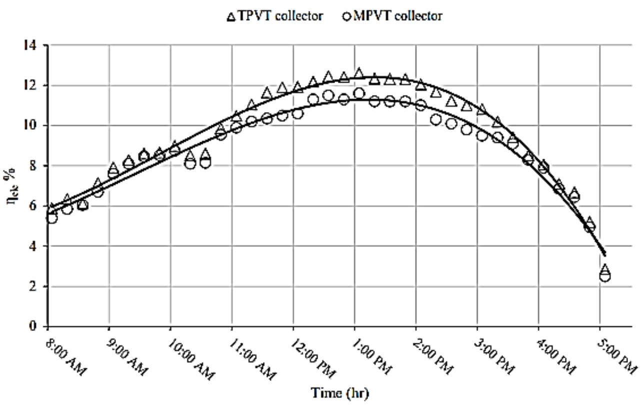


Fig. 5. The PV electrical efficiency variation against time for both systems on February 5, 2020

5.2 When PVT collectors operate with circulating water

a. *Temperature distribution on the PV panel surface.*

The second part of this study began on February 15th and continued until the end of the month. Both collectors were operated with a continuous water circulation of 1 LPM on sunny days. Similar to the previous experience, the weather data was set for February 27 because it featured the best weather during the period, as shown in Fig. 6. The data represents an hourly variation in ambient temperature and solar radiation intensity. It shows that the ambient temperature changes approximately from 9 to 17.5°C, and the maximum solar radiation reaches 365 W/m^2. Fig. 7 and 8 show the temperature distribution on the PV panel of both the TPVT and the MPVT, respectively. They indicated that circulating water has a great influence on the behavior of temperature distribution, which is different from figures 3 and 4. It was observed in the TPVT collector that the temperature difference does not exceed 3°C on the PV panel surface, and the higher level of temperature has occurred at 12:00 p.m., while in the previous experiment, this occurred at 2:00 p.m. This is due to the cooling process of circulating water through an internal heat exchanger. On the other hand, we observed a significant effect of water circulation on temperature distribution in the PVT collector. The temperature distribution on the PV panel increases from x1 to x4 by a large difference at 8:00 a.m., due to the difference between the exiting hot water and the panel temperature. Over time, the temperature on the PV panel becomes higher than exit hot water. The difference temperature distribution was a decrease compared to the corresponding previous case when it was working without water circulation. Additionally, the maximum level of temperature distribution occurs at 12:00 p.m., and the position of the maximum temperature fluctuates with the time between x2 and x3.

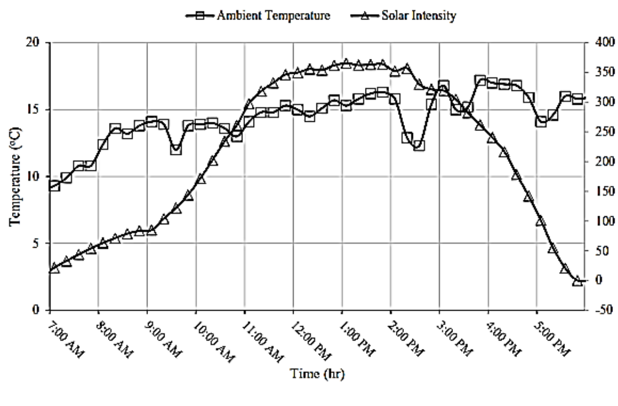


Fig.6. Weather details for the experiment conducted on February 27, 2020.

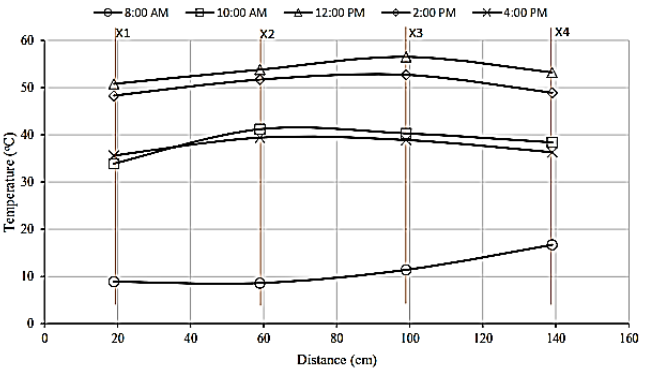


Fig.7. Temperature distribution on PV panel for TPVT collector on February 27, 2020

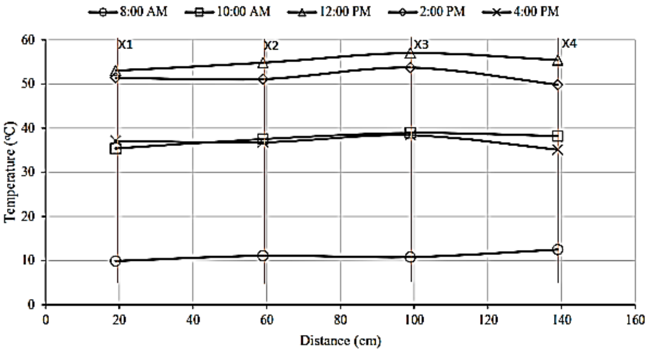


Fig.8. Temperature distribution on PV panel for MPVT collector on February 27, 2020

b. *Thermal energy from hybrid collectors*

In the case of water circulation, both collectors produce electrical energy and heat energy simultaneously. The electrical energy production, in this case, was roughly similar to the experiment on February 5 because there was a large match in solar radiation intensity and ambient temperature for 5 and 27 Feb. So, the electric efficiency was the same as that of the previous experiment in both collectors. For this reason, the efficiency curve has not been repeated. The thermal energy gained by both hybrid collectors, is expressed in Fig.9. It indicates the hourly heat energy gain per unit of the internal heat exchanger area with the solar radiation intensity. We noticed that there is significant time difference in obtaining the maximum useful thermal energy between the TPVT and MPVT collectors. The reason for this is that paraffin wax absorbs energy simultaneously with water from the PV panel when the paraffin wax is in a solid state or its temperature is lower than its melting temperature. As shown in Fig. 7, the useful energy increased rapidly from the beginning of the experiment until 12:00 p.m., when it reached 188 W/m^2 and then slowly decreased against the intensity of solar radiation until 2:00 p.m. After that time, the useful energy dropped significantly. For the MPVT collector, its performance was different from TPVT collector. From start time until 12:40 p.m., it reached a maximum useful energy of about 200 W/m^2. At that time, the thermal energy coming from the PV plate was distributed by the paraffin wax between the useful energy and energy storage, and the energy storage continued until the paraffin temperature become greater or equal to the temperature of the PV panel. It can be seen that from 12:40 p.m. to 1:30 p.m. and until 5:30 p.m., paraffin wax provided the thermal energy to the water.

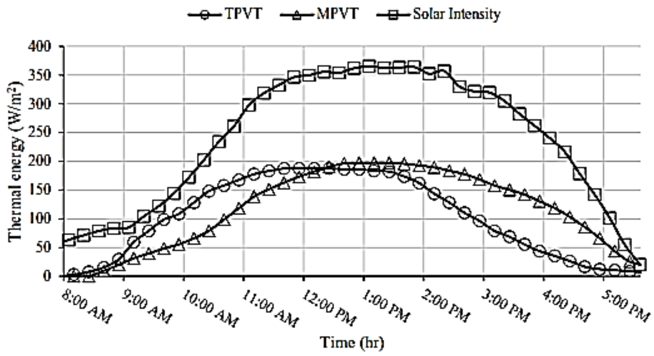


Fig. 9. Thermal energy production against time from hybrid collectors on February 27, 2020.

c. *Total collector efficiency*

The total efficiency of each collector was evaluated, which involved summing the electrical and thermal efficiencies. The electrical efficiency of the TPVT collector was higher than that of MPVT collector. In addition, the thermal energy simulation discussed in section (b) showed that the TPVT collector generated more useful energy than the MPVT collector did between 8:00 a.m. to 12:30 p.m. for the reasons that discussed in the same section, as shown in Fig. 10. This shows that the TPVT collector's efficiency rapidly increased to 94% in the early stage of the experiment but quickly dropped over time until it settled 24.5% at the end of the experiment. This is because the heat exchanger was thin and lightweight, which did not store a large amount of heat energy in its body for a long time and dissipate it gradually into the water. In contrast to the MPVT collector, we added a layer of paraffin wax on the back surface of the heat exchanger store energy outside the heat exchanger body and using it when radiation energy to be dropping. Fig.10 shows that the MPVT collector's efficiency gradually increased from the beginning of the experiment until it reached its maximum efficiency at 12:30 p.m., which was about 67.5%. After that time, the efficiency decreased slightly over time to 58% at the end of the experiment. This behavior results in paraffin property to store and release energy regularly.

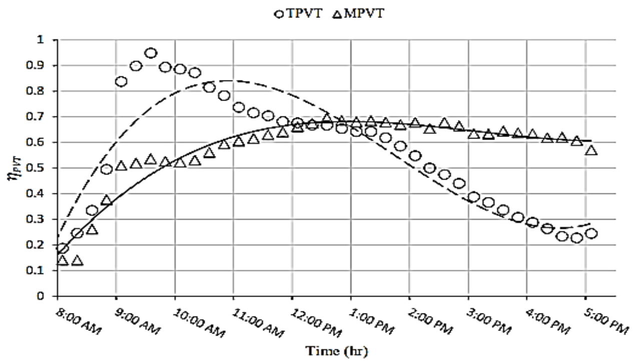


Fig. 10. Overall PV collector efficiency versus time on February 27, 2020

d. Instantaneous efficiency for collectors

The instantaneous efficiency of the collectors was estimated based on ASHRAE Standard 93 (1983), where the data of five days of the experiment (i.e. 25 to 29 Feb.) was simulated. This period included various weather conditions, such as cloudy and sunny days. The thermal efficiency of the TPVT and MPVT collectors was calculated during this period, and the results were plotted against $(T_o - T_a)/G$ according to the above standard, as shown in Fig 11. The observed data in the figure can be seen as a linear relation, which is the best relation to represent this data. The equations of the line shown in the figure are expressed as the efficiency of the collectors. The line showcases the thermal efficiency of the TPVT collector

$$\eta_{th} = 0.5832 - 1.7285(T_o - T_a)/G \quad (10)$$

For MPVT collector, it is thus

$$\eta_{th} = 0.6706 - 0.3217(T_o - T_a)/G \quad (11)$$

When Eqs.10 and 11 are compared with Eq. 8, the intercept of the line with y-axis is represented as $F_R\alpha\tau$,and it is equal to 0.58 and 0.67 for TPVT and MPVT, respectively. But when the slope of the line is represented by the second parameter ($-F_R U_L$) of Eq.8, it is equal to 1.37 for TPVT and 0.378 for MPVT. We notice from Fig.11, that the efficiency of the MPVT collector was slightly affected concerning the variation of the $(T_o - T_a)/G$ parameter compared to the efficiency of the TPVT collector. The MPVT collector's efficiency ranged between 0.67 to 0.6, while for TPVT collector's efficiency was affected significantly by the difference $(T_o - T_a)/G$, due to the high slope of the line efficiency, ranging from 0.58 to 0.27. Fig.11 indicates that paraffin wax has a positive effect on the thermal performance of thermal collectors because it has a good capacity to store thermal energy and release it on demand.

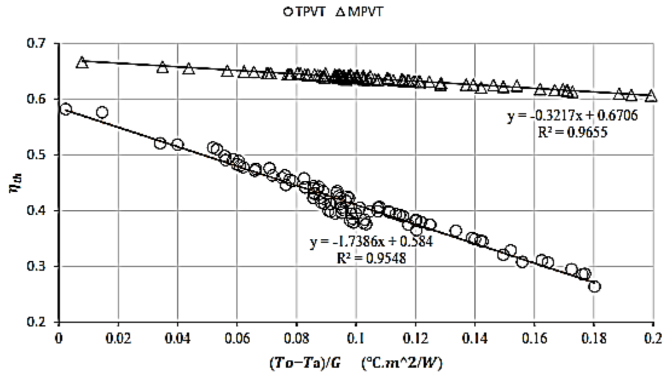


Fig.11. Instantaneous efficiency of the hybrid collectors which were analyzed based on ASHRAE standard 93 (1983)

6. Conclusions

From a series of experiments that was conducted on two hybrid PVT collectors working simultaneously under actual weather conditions in February 2020, the following conclusions have been obtained:

- Adding phase change material to the PV Panel caused decreasing electrical efficiency when it was the only source for electric power generation.
- Adding paraffin wax to the hybrid PVT collector contributed to increasing thermal efficiency, not less than 60%.
- Paraffin wax was considered a good thermal store source, especially if used during afternoon and sunset times when the solar radiation intensity decreases.
- The instantaneous efficiency produced a mathematical relation for each PVT collector and can be predicted for the preliminary planning of the hybrid PVT collectors design.

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