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Spiral Flow Heat Exchanger Effect on Photovoltaic/Thermal System Performance

Spiral Flow Heat Exchanger Effect on Photovoltaic/Thermal System Performance

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Abstract. The photovoltaic modules produce electricity directly by making use of sunlight. However, these modules are clearly affected by atmospheric conditions such as irradiation, temperature, relative humidity and dust. The greater part of the radiation is converted into heat which leads to the heating of the PV module resulting in degradation in the power productivity. In the present research, a spiral heat exchanger was added to the PV module to circulate water forming a PV/T system. This exchanger was welded to the back of the PV panel. The exchanger absorbs the excess heat from the panel and losing it through the cooling water in an outside exchanger. The tests were carried out in Baghdad weather conditions during May 2020. The highest solar radiation intensity measured during the measurement period was 823 W/m^2 while the highest ambient air temperature was 44°C in the shade at 1:30 PM for the day 23/5/2020. The study focused on investigating the effect of the used heat exchanger on the PV/T system's generated parameters. The most important results that were extracted from the study are that the studied PV/T system current was increased by 7.8%, the voltage by 3.3%, the power by 11.48%, and the efficiency up to 21.33% as compared to the photovoltaic panel. The PV/T system produced thermal efficiency ranging from 34.3% at 9 AM to the maximum value of 56.66% at 4 PM. The PV/T system's electrical efficiency in this study was compared with the literature, and it was found that the studied system gave an acceptable electrical efficiency.
Keywords. PV/T, Photovoltaic module, Spiral flow heat exchanger, irradiance, Climate conditions.

1. Introduction

During the past centuries since the Industrial Revolution, the earth's natural resources (such as coal, oil and natural gas) were severely consumed. The great waste of these resources caused a clear decline in it [1]. The aforementioned resources were used extensively in energy production, whether electricity or operating equipment and vehicles. The burning of these materials causes severe environmental pollution and major problems such as the ozone hole, global warming, and dangerous effects on human health, animals and even plants [2]. Thus the whole world started looking for renewable, green, and environmentally friendly resources. However, a big problem was faced due to s the fluctuation of fuel prices in 2008. Since that time, the economies of many producing and exporting countries have not recovered. Renewable energies come from natural sources and these sources are inexhaustible, but because of their renewal, they can always be used in wide applications for the production of electricity. Among these sources are solar, wind, tidal and geothermal energies [3]. Solar energy is the mother of all these energies. Today, it has wide applications in generating electricity and heat. Photovoltaic units are used to directly produce electricity using solar radiation as fuel: it is not depleted, clean, does not pollute the environment, free and available in most parts of the planet. PV modules suffer from high module temperature due to the fact that a large part of the sun's rays goes to heat the module, and a small part of this radiation is used in the production of electricity [4]. High temperature of PV modules have negative effects on current, voltage, power and electrical efficiency. Thus the researchers intend to study the possibility of cooling PV modules to reduce the negative effects as a result of high irradiance rate. The aim of this cooling process is to deliver PV modules to suitable working conditions to produce the highest possible electrical power [5]. The surplus heat in the PV module reaches 85% to 90%, while the electricity produced does not exceed the rate of 10% - 15% of the sunlight incident on the module, depending on the type of solar module used. The excess heat in the body of PV panels increases its temperature, so switching to PV/T systems can reduce the negative effects of this temperature and overcome it [6].

Many studies ihave unanimously agreed that the use of PV/T systems in which the PV module is cooled and the electric power is greater while saving heat energy was wasted in the case of using PV modules without cooling [7]. Ref. [8] designed an energy efficient PV/T system. In this study, the cooling process of the solar module was evaluated depending on the electricity generation efficiency. The results showed an increase in the electrical efficiency of the designed system by about 15% as compared to PV panels due to the uniformity of cooling. Ref. [9] studied a system employing a heat pump connected to a water heating system and a PV/T system cools this system with air. The researchers concluded that there was a clear increase in the performance of the PV/T system as compared to the PV panel. The studied PV/T system produced higher electric power than using PV panel and provided thermal efficiency of 30.28%, bringing the overall system efficiency up to 46.89%. Ref. [10] technically and economically studied a PV/T system uses cooling by circulating a nanofluid through a tank containing a mixture of paraffin wax (PCM) and nano-SiC. The nano-SiC was added to improve the used paraffin's thermal conductivity. The used PV/T system efficiency reached a high value of 13.7%, while the system's thermal efficiency has reached 72.0%. From an economic point of view, the study found that the payback period for this system is limited to between 5 to 6 years. Ref. [11] investigated a grid connected PV/T (GCPVT) system cooled with nanofluids in climatic conditions of Malaysia both theoretically and experimentally. The economic evaluation of the studied GCPVT system demonstrated that the payback period ranged between 7 to 8 years, and the annual production factor ranged from 128.34 to 183.75 kWh / kWh. As for the energy cost, it did not exceed 0.196 USD / kWh. The study results depicted that the PV/T system's maximum electrical efficiency achieved was 9.1%. The conclusion of the study is that the GCPVT system showed a clear enhancement in the system's economic performance. Ref. [12] studied reducing PV temperatures and reaching the temperature within permissible limits by cooling them with water that circulates in a heat exchanger installed at the back surface. The results of the study showed that the cell temperature is proportional to the negative exponent of the water flow rate, and that increasing the water flow rate to high levels causes an increase in energy consumption. Ref. [13] used water to cool the PV panel to increase the efficiency of the studied PVT system. For this purpose, the researchers used two different refrigerants, such as R600a and R290. The results show that increasing the water mass flow rate enhances the overall efficiency of the PVT system, raising it from 66.7% to 75.8%. Ref. [14] developed a water flow through a copper tube that enables the absorption of the oscillation in irradiance. The researchers adopted the experimental data and entered it into the MATLAB program and verified the validity of the numerical simulation with the experimental results. The study concluded that the highest electrical efficiency that a PVT system can be achieved is 11.5% when the water flowrate was 6 l/min. The maximum thermal achieved efficiency was about 58.64% at a water flowrate of 5 l/min.

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Ref. [15] studied three PVT water cooling systems with variable flow channels (web type, direct type, and spiral type); their performance was evaluated and compared to a PV system. The four systems were tested in the Omani city (Sohar) external weather conditions. The study concluded that the highest average voltage, current and power of a PVT system with a spiral flux heat exchanger were 17.7 volts, 2.89 amps, and 51.3 watts, respectively. The study concluded that the spiral flow system produces the highest electrical efficiency as compared to other studied systems. Ref. [16] studied a heat exchanger model used for cooling PV systems consisting of a number of tubes shaped like (U tube). The researchers used a mixture of glycol and water as a coolant. The researchers studied the effect of the number of U tubes in the heat exchanger and the mass flow rate of the cooling fluid on improving heat transfer. The simulation and practical results show good agreement. The study concluded that reducing the temperature of PV systems increases the overall efficiency of the entire system. This practical investigation aims to evaluate the impact of irradiance and PV temperature on its performance. In this study a spiral flow heat exchanger was used in a PV/T system practically, and tests were conducted on PV/T system to evaluate its performance and efficiency. The study aims to introduce an efficient PV/T system using water as cooling fluid.

2. Experimental setup

Figure 1 (a & b) shows the various parts of the proposed system utilized in the experimental tests (schematic and a photo). Two PV panels (polycrystalline silicon) made by **(**Kyocera KD140GH-2PU) were utilized. They have 3.4 A, 21.03 V, 50 W, 1.5 kg weight and 415×268×22 mm^3. Five thermocouples type K were used to evaluate the PV panels' surfaces temperature and the flowing water temperature (at the heat exchanger's inlet and outlet). The used thermocouples were calibrated; their uncertainty was evaluated, which was about 0.03 K through all the range of measured temperatures. Water flow rate was measured using flowmeter sensor. In the studied system, a pump was used to circulate the cooling water. This pump takes the electricity necessary for its operation from an external source, in order to be able to limit all the productivity of the photoelectric panel with the studied factors and not to be interfered with the required power of the pump. In this study, a spiral type heat exchanger was used instead of a solar collector (Figure 2 shows a diagram of this exchanger). The spiral flow exchanger was manufactured with aluminum tubes and dimensions are equal to that of the used PV panel (415 x 268 mm^2). The spiral heat exchanger was 4 m long and has a tube diameter of 1.25 cm of a tube thickness of 1.25 mm. The heat exchanger was fabricated according to the method used by Reference [15] as well as in selecting the heat exchanger tube measurements. This exchanger was welded to the back of the PV panel. Silicone oil was also added to the back of the PV panel to fill in the spaces between the cell and the exchanger, whose presence causes poor heat transfer from the PV panel to the exchanger.

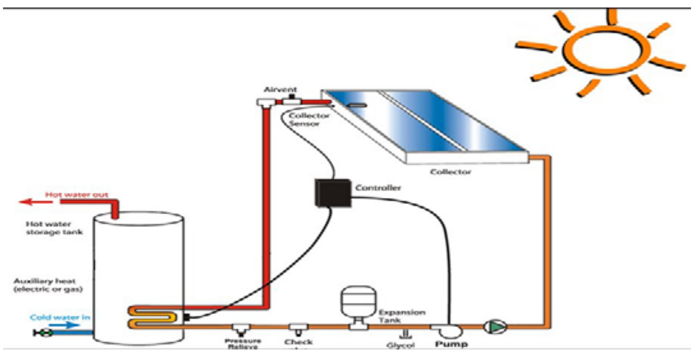

Figure 1. Schematic diagram showing the different parts of a PV / T system.

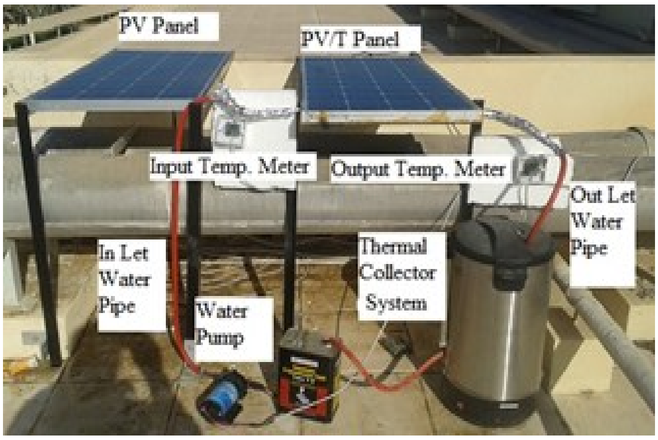

Figure 1b. Real system picture.

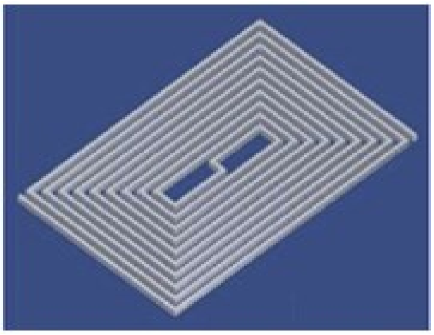

Figure 2. Schematic diagram of the (spiral flow) heat exchanger used in the study.

Several mathematical relationships have been used to find the systems' performance.
The heat flow rate is:

$$Q_u = m \times C_p\ (T_o\text{-}T_i)$$

Where; m: represents the water mass flow rate, C_p: indicates the specific heat of water (J/kg K) while T_o and T_i: are the measured temperatures of the outlet and inlet of the heat exchanger (°C).
The PV/T system's thermal efficiency is calculated by:

$$\eta_{th} = \frac{Q_u}{I_s \times A_c}$$

Where; I_s ; The irradiance (W/m^2), A_c: Area of proposed collector (m^2).
Power (W) is evaluated using the relationship:

$$P = I \times V$$

The electrical efficiency (%) of the PV panels is evaluated by:

$$\eta_e = \frac{P}{I_s \times A}$$

Where; A: The area of the photovoltaic panel (m^2).
The overall efficiency of the proposed PV/T is calculated by:

$$\eta_{total} = \eta_e + \eta_{th}$$

Table 1 lists the measuring equipment and devices specifications.

Table 1. The measuring devices and equipment specification.

Parameter	Brand/ Name	Range	Uncertainty
Solar irradiance (G)	BF5 Sunshine sensor	0-1250 W/m^2	±5 W/m^2, ±15%
Temperature (PV module, PV/T collector, inlet, and outlet)	Thermocouples (Type K)	−200 °C to +1350 °C	±1.09 °C
Flow meter sensor	US Hunter	0.83-80 l/min	25, 40, or 50mm BSP Flow Meter
Water pump	RONDA	DC12V/24V, 1-6 l/min (0.26-4.2US.GPM)	
Multi meter (Current and Voltage)	CEN-Tech	DC Voltage from 20 mV to 1000 mV. DC current from	±0.35%
Multi meter (Current and Voltage)	CEN-Tech	DC current from 20mA to 20 A	±0.25%

2.1. Test procedure
The experiments were conducted in May 2020, at a rate of three days a week. The selecteddays were with clear skies without rising dust or clouds. The studied photovoltaic surface temperatures, the temperature of the water entering and leaving the heat exchanger, the irradiance, and the ambient air temperature were measured and read. Both the current and the voltages were measured with the loading of the two systems using a variable resistance in these conditions. All results shown are the arithmetic mean of all measures.

3. Results and discussion
In this study, the outdoors tests were conducted in Baghdad weather conditions in May 2020. The used cooling water flow rate was 0.13 kg/s depending on the results of references [10 & 12]. Figure 3 shows the different temperatures measured for the two systems tested. The air temperature reacheed its maximum (41°C) at about 2 PM while its average did not fall below 33°C throughout the days of the tests. As for the surface of the PV cell, its temperature exceeded 56°C at 2 PM, and throughout the time it did not fall below 35°C. The high temperatures caused poor performance of this system. For the PV/T system, the maximum temperature reached by the photovoltaic panel is 43.6°C. For a full day operation, the cooling efficiency was around 16%. As for the temperature of the water entering and leaving the heat exchanger, the difference ranged from 5°C at noon hours to 15°C in the early morning hours. The efficiency of the heat exchanger is appropriate and efficient, noting that the cooling fluid used is water that has low thermal conductivity.

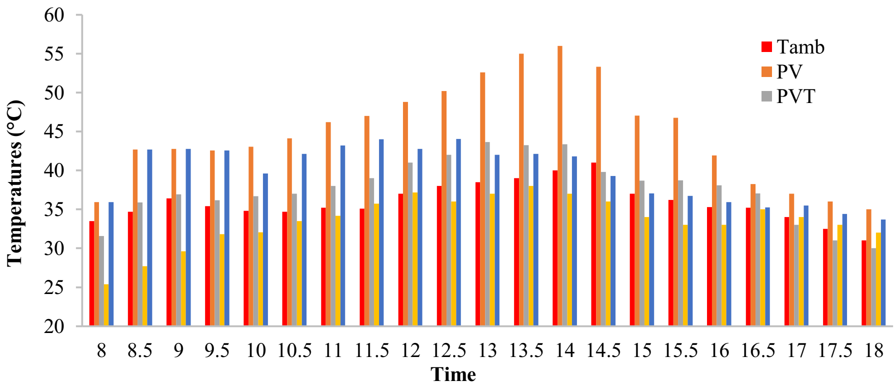

Figure 3. Variable temperatures variation wit time.

Figure 4 describes the DC current generated by the PV module which changes during the hours of the day due to the change in solar radiation. The time advance from the early morning hours (where the radiation intensity is low as well as the air temperature) to noon (when the radiation intensity and the air temperature reach their peak) means that many changes in the temperature of the photovoltaic panel will occur. This rise in irradiance and temperature of the PV panel cause a decrease in the current generated during the work of a PV in peak hours from 12 AM to 2 PM. The results show that the measured PV current is less than the PV/T system as an inevitable result of cooling the PV module with water that causes significant decrease in the temperature of the PV system. The efficient cooling of the PV/T system results in increasingthe current produced by approximately 7.8% for full-day operating hours (8 AM to 6 PM).

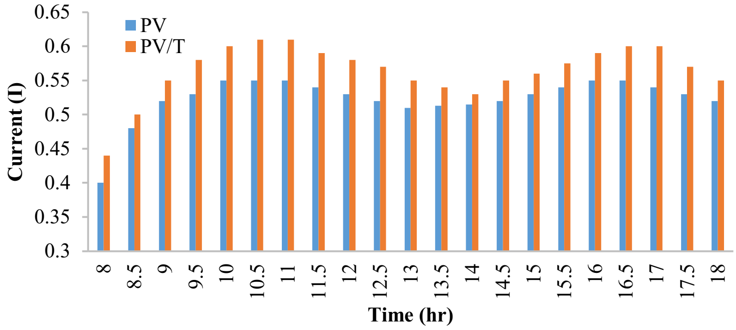

Figure 4. The current changes over time for the studied systems.

Many documented studies have concluded that the increase in irradiance intensity negatively affects the voltage of the PV modules. Thus, cooling the PV modules has a positive effect on these voltages. The positive effect of cooling the PV panel was clearly observed when testing the proposed PV/T system. Cooling the PV module resulted in an increase in the DC voltage generated, and this effect increased in the evening as shown in Figure 5 . The ambient temperature and the cooling water temperature reduced as in Figure 3 . These two factors caused a clear rise in voltage. The proposed PV/T system generates about 3.3% more voltage throughout the day what than the PV system does. Figure 6 shows the electrical DC power generated during the day. The PVT system's generated power increased during the morning hours until 11 AM, as the maximum achieved power was 13.1 W at that time. Then, at the solar irradiance peak hours (12 AM to 2 PM), the PV/T system power decreased as the minimum power reached was 11.4 W at 2 PM. The power increased again during the evening hours (3 PM to 6 PM) as a 12.4 W was achieved at 4 PM. During peak hours (from 12 AM to 2 PM), there was a decrease in the productive power of up to 15% due to the high irradiance that causes an increase in the temperature of the PVT system panel. When the system was running for a continuous day, the results showed an increase in the PV/T system's power up to 11.48% as compared to the PV system. This increase in the power generated can be attributed to the good cooling of the PV panel using water and a spiral heat exchanger.

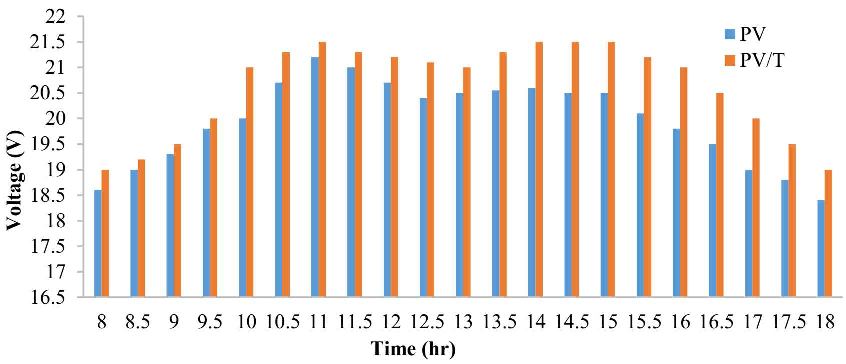

Figure 5. The voltage changed over time for the PV and PV/T systems.

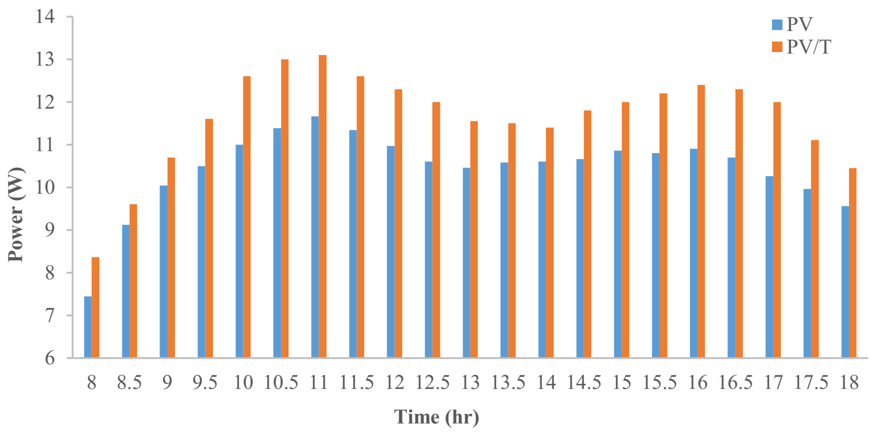

Figure 6. The power changed over time for the PV and PV/T systems.

Figure 7 shows the variable efficiencies of a PV/T system (total, electrical, and thermal) while a PV system produces electrical efficiency only. The efficiencies shown in the figure were obtained from 8 AM to 6 PM operation of the systems. The PV/T system's electrical efficiency was larger than the photovoltaic system throughout daily operation time because of the PV/T heat exchanger cooling. The increase in electrical efficiency of PV/T system was about 21.33% as compared to PV system for daily operation. The thermal efficiency resulting from the cooling process of the PV/T system was several times higher than the electrical efficiency. The maximum thermal efficiency reached by the PV/T system was 50% at 4 PM. The total efficiency of the PV/T system ranged from the lowest value of 34.3% at 9 AM to the maximum value of 56.66% at 4 PM. The above results show that the studied PV/T system has a high cooling efficiency that results in an electrical output surge (current, voltage and power).

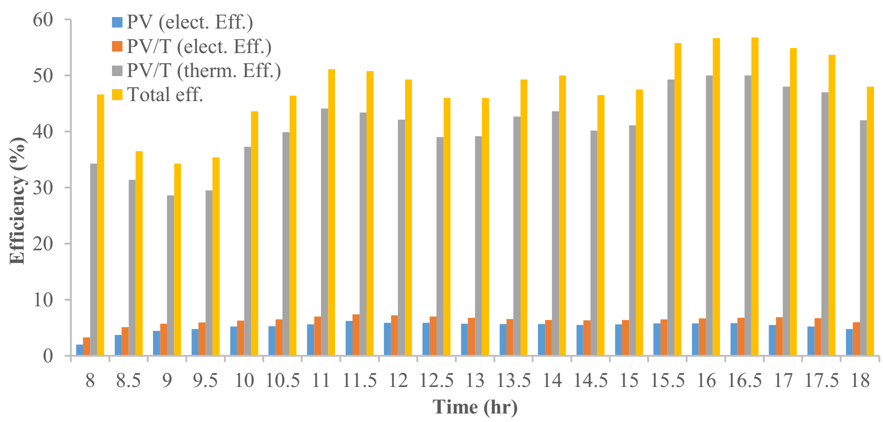

Figure 7. The studied systems electrical variations with time.

In Figure 8, a comparison is made with a number of studies in the literature. It was based on the electrical efficiency produced by each PVT system. Certainly, this comparison may not be fair to some studies due to the variation in the heat exchanger type, solar collector design, and the PV module type, in addition to the variations in the type of coolant. The proposed PVT system in this study obtained electrical efficiency of (7.4%) employing water cooling, and a spiral heat exchanger, [17-37]. The proposed system gave good results as compared to systems that used water as a cooling fluid, such as references [17, 20, 21, 23, 24 and 32]. For studies that obtained higher electrical efficiency in the range of 8 to 9%, nanofluids were used to cool the PVT systems as in references [18, 19, 26, 30, 32, 33 and 37]. As for the systems that obtained electrical efficiency higher than 10%, they used different nanofluids in addition to nano-PCM which caused a rise in the cooling effect as in references [20, 21, 22 and 35]. The comparison in the figure shows that the proposed system is of high efficiency taking into consideration the cost. Furthemore, water in any case is cheaper than nanofluids and nano-PCMs, and is more commonly used.

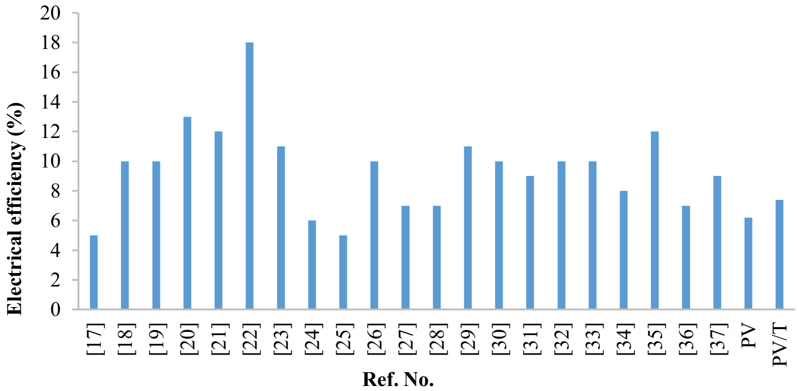

Figure 8. The studied PV/PVT electrical efficiencies as compared to several systems in literature.

4. Conclusions
The high irradiance rate of the Baghdad city increases the temperature of the PV module significantly which results in a sharp reduction in power. The current study employed a water cooling PV/T system utilizing a spiral flow type heat exchanger welded to the PV panel's back. The circulating water inside the spiral heat exchanger cooled the PV module. The used exchanger succeeded in raising the current up to 7.8%, the voltage by 3.3%, and the wattage up to 11.48% as compared to the PV module used. The electrical efficiency of the PV/T system increased by 7.4%, as compared to the maximum efficiency of the PV system, which reached 6.2%, with an increase of 19.35%. When compared to operating the two systems for a full day, the increase obtained in the electrical efficiency of the system PV/T amounted to 21.33%. The PV/T system gave a maximum thermal efficiency of 50% at 4 PM. The maximum total efficiency was obtained; it was 56.66% at the same previous time. Following the results of the present investigation with literature, the proposed heat exchanger resulted in lower electrical efficiency than the systems proposed by some researchers at a good rate as compared to those who used nanofluids or nano-PCM PV/T systems.

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