Performance Assessments of Direct Contact Serpentine Tube Based Photovoltaic Thermal Module: An Experimental Comparison

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Article Info	Abstract
	Solar energy is the most focused in the field of renewable energy. It is a clean, green, environmentally friendly energy source. One of the modern technologies utilized by researchers to investigate the wasted heat by the photovoltaic module is the photovoltaic thermal collector, which simultaneously provides thermal and electrical power for various engineering applications. This study presented a new configuration of a water-cooled photovoltaic thermal module that utilizes a copper serpentine tube attached directly using thermal silicon to the poly-crystalline PV module for water circulation. The created PV/T was well-insulated using fiber material, insulation cork, and Wooden parts. The water flow was circulated via a DC pump with low power consumption. The fabricated unit was compared to the standalone photovoltaic module for the performance evaluation. The main result showed a significant enhancement in the electrical productivity of the photovoltaic thermal module compared to the standalone unit. The cell temperature was reduced by 13.3% compared to the standalone photovoltaic module. Accordingly, the water-based PV/T module effectively eliminated the heat dissipated to the surrounding region by the PV module by using a serpentine tube, assuring sustainable contribution.

1. Introduction

In recent decades, there has been considerable focus and advancement in reducing the use of fossil fuels to establish a completely sustainable energy system by minimizing the overall demand for primary energy [1]–[3]. The rising apprehension regarding energy sources and their utilization has subsequently amplified the fascination with photovoltaic thermal (PV/T) collectors [4]. The origins of the groundbreaking research can be attributed to Wolf (1976) [5].

Subsequently, PV/T has been thoroughly investigated, and a substantial body of studies has been conducted over the past period [6]–[8]. Nevertheless, an examination remains active regarding the design of the structure, the course of fabrication, and the promotion of the product in the market [9]. Studies have shown that water-based photovoltaic thermal WC-PV/T collectors can achieve greater overall efficiency, which has led to their widespread acclaim [10],[11].

As the cell temperature is the most common issue affecting significantly the conversion efficiency of the Photovoltaic (PV) module [12], Various researchers have made efforts to mitigate the adverse impact of cell temperature of the PV modules through the implementation of diverse methodologies and configurations.

A variety of PV/T unit setups were studied by Ibrahim et al. [13] utilizing various shapes of the water circulation tube. This collector is a flat-plate design that uses a single sheet of glass for heat transfer. It was discovered that the most efficient design was the spiral flow design. A single sheet of glass operating at a flow rate of 0.01 kg/s resulted in the highest heat efficiency of 50.12% and the highest cell efficiency of 11.98%.

Dupeyrat et al. [14] analyzed the efficiency of a flat plate-based PV/T unit with single glazing. A primitive two-dimensional thermal model was utilized to investigate different forms of enhancements. The designed arrangement achieved a thermal, electrical, and overall efficiency of 79%, 8.8%, and 88%, respectively.

In their study, Khelifa et al. [15] developed a thermodynamic model for a steel sheet attachment. They supply cold water through tubes under the solar panel to remove heat for a more efficient photovoltaic thermal module. To understand how hot it becomes and the movement of water in their system, they used ANSYS14 software.

Another study by Kazemian et al. [16] investigated how the presence of a layer of glass and the type of coolant affect the performance of PV/T units in terms of electrical and thermal energy. Their field experimental tests used two identical PV/T systems, one with a glass cover and another without it. Based on the results obtained through their experiments, they found that glazed PV/T was less electrically efficient than the unit without a glass cover.

Abdullah et al. [17] examined an indoor water-cooled PV/T system unit experimentally. Their experiment employed a new dual oscillating metal absorber integrating copper pipes, and the findings of their result were compared with those of a classical PV module. The results clarified that the increase in the mass flow rate leads to a decrease in cell temperature and an enhancement in electrical efficiency. Also, they found that the optimal mass flow rate and radiation were 500 w/m2 and 0.1 kg/s.

Several modern techniques were conducted by researchers to confirm heat extraction from the PV cells within the construction of the photovoltaic thermal module systems. Experimentally, Javidan and Moghadam [18] created a liquid nozzle array fixed into a special glass box under the PV module to cool the solar cells. The heat exchange liquid goes through the piping system fixed within the glass box for further application. The result proved the potentiality of their methodology to enhance the photovoltaic thermal performance through multi-orifice nozzles.

In contrast to the study of Javidan and Moghadam [18], Raju et al. [19] experimentally and theoretically created a set of water plastic nozzles above the PV module to confirm the cooling of the solar cells. Through a flow rate from 0.02 kg/s to 0.14 kg/s, the electrical efficiency was enhanced by more than 5.17 %.

Another PV cooling technique, Yoon et al. [11] proposed a radiative cooling technique by utilizing the thermosyphon effect using a large water storage tank. Through their experiments, the results indicate that the suggested system is suitable for dry and hot sites where there is a significant difference between the highest and lowest temperatures during the day.

Majeed et al. [20] fabricated a new cooling system using an underground heat exchanger to circulate water into a spiral copper pipe fixed to the back side of the solar cell module. The main finding of their results indicates an enhancement of the electrical efficiency by 127.3% compared to the classical unit.

Brahim et al. [21] introduced a computational approach to test the influences of wind speed, incoming sunlight, temperature of intake water, tube quantity, and area on the performance improvement of solar panels. The findings of their computational model indicate that a decrease in incoming radiation, an increase in wind speed, and a decrease in outside temperature led to enhanced electrical efficiency.

Bae et al. proposed a low-cost absorber that can be attached to the back side of the old PV modules to configure a new WC-PV/T. The consequences of their study presented low-cost and low-emission technologies to simplify the usage of PV/T units in further applications.

Based on the preceding discussion, research papers are scarce in the literature about the utilization of a direct-contact serpentine tube (DCST) with the PV module for water circulation. This study fabricated a new water-cooled photovoltaic thermal unit by attaching a copper serpentine tube that adhered directly to the PV module's rare side. The fabricated PV/T module was compared to the standalone unit regarding the electrical productivity and cell temperature.

2. Experimental Methodology

2.1. Fabrication Setup

The solar panels provided and evaluated in this research have been placed in the University of MATE, Institute of

Technology, Solar Energy Lab, Hungary, Gödöllő. The map coordinates of the study location are: (47.594251, 19.366645). Additionally, the system was installed at tilt and azimuth angles of 43° and 20°.

A poly-crystalline PV module specified in Table 1 was utilized to configure the new unit of the PV/T.

Table 1. Specification of the PV module

Details	Amount
PV cell type	Poly-crystalline
Area	0.55m
Model	M S X~60
Max power	60 W
Max Voltage	17.1 V
Max current	3.5 A
Temperature coefficient	±0.05 °C

A special thermal silicon was utilized to attach a copper serpentine tube directly to the PV surface. Fig. 1 shows the fabrication of the serpentine tube. Fig. 2 illustrates the adhering of the serpentine tube to the rare side of the PV module.

Figure 1. Fabrication of the serpentine tube
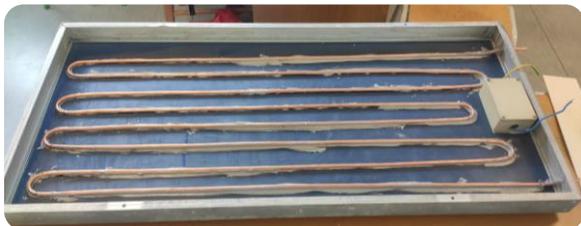
Figure 2. Adhering of the serpentine tube to the PV module. This study utilized fiber material, insulation cork, and wooden parts to create a well-insulated system for the proposed unit of

the PV/T module. Fig. 3 shows the isolating and the final configuration of the new water-cooled module.
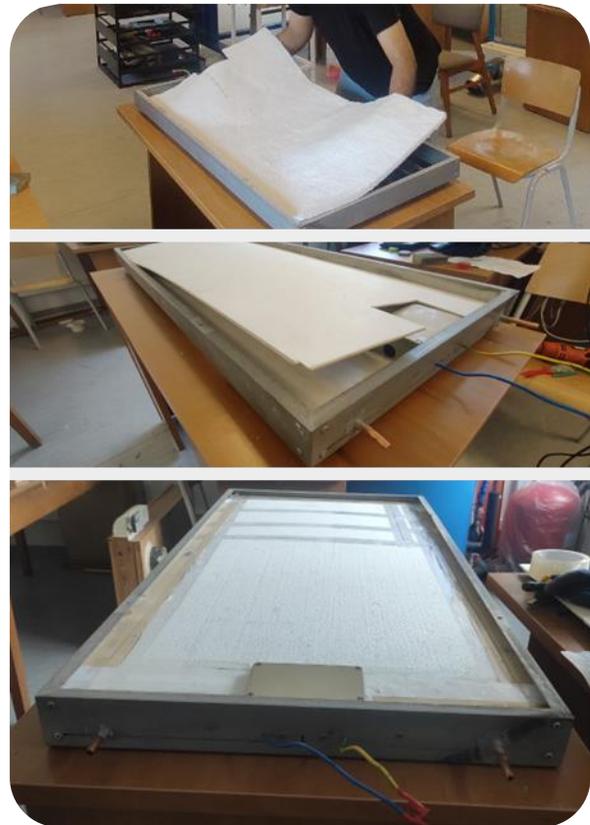
Figure 3. Isolating and the final configuration of the presented PV/T.

Finally, the final actual view of the proposed units in this experiment, PV and PV/T units, is exemplified in Fig. 4.

Figure 4. Actual view of the modules.

2.2. Data Gathering

The following factors were observed at regular intervals of 5 seconds during the experiments that began at 09:00 and ended at 15:00 on August 15, 2023:

- Solar radiation
- The inlet temperature of the coolant fluid.
- Outlet temperature of the coolant fluid.
- Solar cell temperatures of the two modules
- Surrounding temperature.
- Water flow rate.
- Modules' currents and voltages.

An Arduino data logger was used to gather data, and several sensors were used for electrical and thermal purposes. Table 2 illustrates the data logger and sensors used to record the data during the study period. Fig. 5 shows the positioning sketches of the apparatus listed in Table 2 through the study modules.

Besides, the systems circulated the water through the serpentine tube via a DC pump with 4.5 W controlled consumption power to ensure the laminar flow pattern into the system tube with a Reynolds number of 2098. This study utilizes this pump at a fixed flow rate of 0.017 kg/s. Because of the low power consumption of the pump and because this pump serves the building more than the system itself, this power is neglected in the calculations.

Table 2. Specification of the data logger and sensors used to record the study parameters.

Apparatus	Purpose	View, Un
Manufactured Arduino	Data logger	
Pyranometer-Mess-kopf-3.3	Solar radiation	
DS-18/B-20	Temperature Sensor	± 0.5 %
Digital electronic resistor	Currents Voltages	± 0.4 %
YF-S-402	flow rate	± 0.2 %
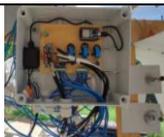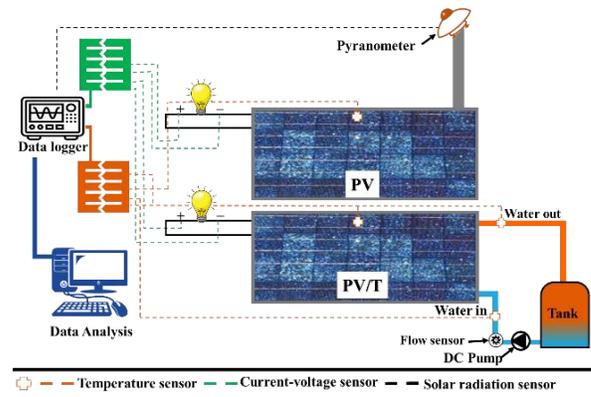
Figure 5. Positioning scheme of the sensors.

2.3. Performance Assessment of the Modules

The electrical efficiency (η_{el}) is an essential factor of the performance assessment of the solar energy units, and it can be originated using Eq. 1 [22].

$$\eta_{el} = \frac{P_{el}}{E_{in}} \tag{1}$$

The electrical power (P_{el}) of the study modules could be calculated by Eq. 2 [23]:

$$P_{el} = I\,V \tag{2}$$

where I is the output current, and V is the output voltage of modules. The input power (E_{in}) of the solar energy system is the solar radiation investigated by the full area of the solar cells and could be identified by Eq. 3.

$$E_{in} = G * A_M \tag{3}$$

G is the solar radiation, and A_M is the solar cell module area.

Besides, the thermal efficiency (η_{th}) of the PV/T module could be determined by Eq. 4.

$$\eta_{th} = \frac{Qu}{E_{in}} \tag{4}$$

The fluid heat-gain (Qu) formula is:

$$Qu = \dot{m}_f Cp_f (T_{f,o} - T_{f,i}) \tag{5}$$

where mass flow rate and specific heat are $\dot{m}_f$ and Cp_f. $T_{f,o}$ and $T_{f,i}$ are the outlet and inlet temperature of the fluid.

2.4. Uncertainty analysis

Due to the precision of the data-recording instrument and apparatus, as listed in Table 1, uncertainties analysis for potential error for the recorded outcomes has been accomplished.

The tested parameters are the temperature for the inlet and outlet of the heat transfer fluid, the electrical power parameter, and the radiation.

According to Holman [10], the module efficiencies were subject to the uncertainty analysis:

$$U_R = \left[\left(\frac{\partial R}{\partial x_1}\right)^2 Un_1^2 + \left(\frac{\partial R}{\partial x_2}\right)^2 Un_2^2 + \cdots + \left(\frac{\partial R}{\partial x_n}\right)^2 Un_n^2 \right]^{1/2}$$

(6)

where U_R is the uncertainty and x is the equation's variables. Accordingly, the thermal efficiency uncertainty ($U\eta_{th}$) and electrical efficiency uncertainty ($U\eta_{el}$) could be calculated using the equations (7) and (8), respectively.

$$U_{\eta_{th}} = \left[\left(\frac{\partial \eta_{th}}{\partial T_{out}}\right)^2 (U_{T_{out}})^2 + \left(\frac{\partial \eta_{th}}{\partial T_{in}}\right)^2 (U_{T_{in}})^2 + \left(\frac{\partial \eta_{th}}{\partial G}\right)^2 (U_G)^2 \right]^{1/2}$$

(7)

$$U_{\eta_{el}} = \left[\left(\frac{\partial \eta_{el}}{\partial I}\right)^2 (U_I)^2 + \left(\frac{\partial \eta_{el}}{\partial V}\right)^2 (U_V)^2 + \left(\frac{\partial \eta_{el}}{\partial G}\right)^2 (U_G)^2 \right]^{1/2}$$

(8)

Therefore, Table 3 indicates the calculated uncertainties of the primary parameters used in this study.

Table 3. Uncertainty values of the parameter.

Module	Electrical efficiency	Thermal efficiency
PV	±0.687%	-
PV/T	±0.674%	±0.686%

3. Results and Discussions

This investigation was conducted on August 15, 2023, methodically emphasizing outdoor experimentation, and from 9:00 to 15:00, the experimental period transpired under optimal atmospheric conditions characterized by clear skies and unimpeded solar radiation. Throughout this period, the study systematically documented an average solar irradiance of 914.7 W/m² while concurrently monitoring an ambient temperature of 31 °C, as delineated in Fig. 6. These precise environmental observations yield crucial insights into the operational dynamics and performance metrics of the systems under scrutiny, showcasing the scientific rigor and methodological precision inherent in this research endeavor.
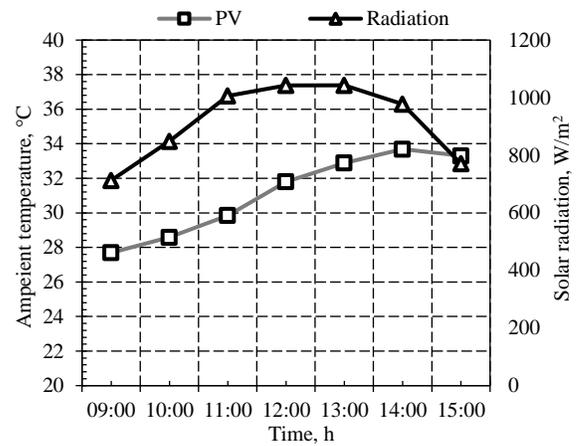
Figure 6. Positioning scheme of the sensors.

The literature on photovoltaic modules focuses significantly on cell temperature, a parameter of great interest and importance. In this assessment, particular attention was given to measuring the cell temperature of the investigated modules. Depicted in Fig. 7, elucidates the comparison of these temperatures of solar cells concerning solar radiation. Notably, the maximum cell temperatures recorded for the modules are 62 °C and 54 °C for the standalone PV and WC-PV/T modules, respectively. These findings underscore the impact of thermal management strategies, such as water cooling, in mitigating cell temperature rise and enhancing the overall performance and longevity of the PV system.
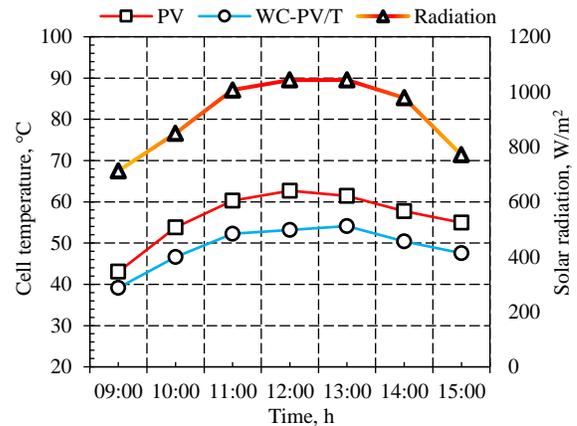
Figure 7. Cell temperatures with radiation.

As clarified in the above figure, the temperature of the WC-PV/T solar cell has been recorded at lower values than that of the PV modules. This temperature reduction proves the efficiency of the cooling technique created in the fabricated PV/T module compared to the classical unit.

Fig. 8 clarifies the electricity generation of the units used in this study, as well as their relationship to incident radiation.

As graphically proved based on the figures, the new water-cooled module introduced more electrical productivity. The average electrical power is 30 W and 25.8 W for the water-cooled and standalone PV units.

Following the fact confirmed through literature, there is a correlation between the reduction of cell temperature and the rise in electrical efficiency. This relationship is depicted in Fig. 9, where the electrical efficiencies of the modules are plotted. On average, the electrical efficiency is measured at 7.3% for the water-cooled PV units and 6% for the standalone PV units. This data underscores the significance of temperature management in achieving higher electrical efficiencies in photovoltaic systems.

In addition to its electrical productivity, the system simultaneously generates thermal power, leading to the designation of the fabricated unit as a hybrid solar collector due to its dual power generation capabilities. This innovative feature not only enhances energy output but also contributes to cost and area reduction, making it an attractive solution for renewable energy systems. As illustrated in Fig. 10, this is a comprehensive overview of the heat gain and electrical generation achieved through this technology. Remarkably, the maximum thermal power recorded in this module surged to 310 W, showcasing the efficiency and versatility of the hybrid solar collector design.

Figure 9. Electrical efficiency of the module.
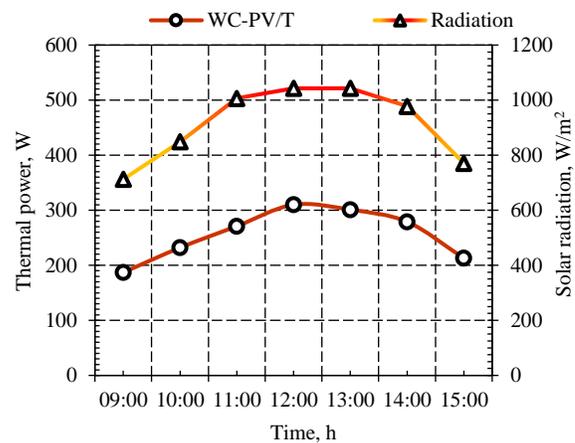
Figure 10. Heat gain of the module.

Figure 8. The electrical power of the modules.

4. Conclusions

This study fabricated a new photovoltaic thermal module utilizing water as a coolant which circulated through a direct-contact serpentine tube mounted to the PV module. Accordingly, this study declares several significant viewpoints and conclusions held behind the methodology. A noted rise in electrical productivity was obtained for the water-based PV/T unit compared to the standalone PV units. The electrical power of the units is 30 W and 25.8 W, respectively. Seqcuenelly, the electrical efficiency of the study modules is 7.3% and 6%, respectively. The fabricated water-cooled unit provides a thermal power of 310 W, which confirms that the fabricated water-based PV/T unit successfully removed the transferred heat by the PV to the surrounding area as a result of using a serpentine tube and ensuring sustainability contribution. As a result of using a serpentine tube, the cell temperature was reduced by 13.3%.

As stated in the results, the cooling technique utilized in this research has a positive potential in the enhancement of the

photovoltaic thermal module performances. However, the field of the presented module in this study is still open to further suggestions, especially the reconfiguration and the utilization of a high thermal conductivity coolant like nanofluids.

Acknowledgments

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Ahssan M.A. Alshibil: Conceptualisation, Methodology, Formal analysis, Investigation, Writing - Original Draft.

Viktor Erdélyi and János Tóth: Methodology; manufacturing of the gathering data acquisition.

Piroska Víg: Conceptualisation, Methodology, Review & Editing, Supervision.

István Farkas: Conceptualisation, Methodology, Supervision, Review & Editing.

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