The Hybrid Energy Performance of a Water-Based PVT Collector with Twin Spiral Configuration

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Received: 14 July 2025 | Revised: 8 August 2025 | Accepted: 20 August 2025

ABSTRACT

The increase of the Photovoltaic (PV) temperature can reduce the PV efficiency. However, with Photovoltaic Thermal Technology (PVT), the heat contained in the PV module can be utilized to produce useful heat, and at the same time enhance the PV electrical energy. In this research, the twin spiral configuration PVT collector performance is assessed. The surface temperature of the twin spiral configuration model PV module and the outlet water collector temperature in steady state are analyzed using Computational Fluid Dynamics (CFD) simulation. The temperatures are then used for calculating the PV electrical efficiency and solar collector thermal efficiency. With water flow variations between 0.01 kg/s and 0.05 kg/s, and solar intensities of 500 W/m², 600 W/m², 800 W/m², and 1000 W/m², the PVT performance was analyzed. This study shows that the electrical efficiency achieves its highest value of 15.43% at 500 W/m² irradiance intensity and 0.05 kg/s water flow, with an average PV module temperature of 33.86 °C. While the Thermal Efficiency (TEF) reaches its maximum value of 81.55% at the irradiance intensity of 1000 W/m² with 0.05 kg/s water flow, and the average water output temperature was 32.3 °C. In general, at solar intensity variations greater water flow contributes positively to the improvement of PV electrical and solar collector thermal efficiency.

Keywords-photovoltaic temperature; computational fluid dynamics; twin spiral; electrical efficiency; Thermal efficiency

I. INTRODUCTION

As the PV module temperature rises, its performance efficiency decreases in generating electrical energy [1, 2]. PVT systems absorb the heat generated by the PV cells for subsequent use, thereby lowering the PV module temperature and mitigating the PV thermal issue. This process increases the electrical efficiency and generating thermal energy in the same time, so the overall system efficiency can be enhanced [3]. The PV module temperature can be reduced by making use of the heat produced by the PV for air heating or domestic hot water, which is the working principle of the PVT system [4, 5]. The utilization of shared frames and brackets reduces the equipment prices and space requirements, giving this system an advantage over standalone PV and solar thermal systems.

Research into the PVT system design and innovation continues to improve the efficiency of the thermal and electrical performance. In general, the assessment of PVT performance is focused on its electrical power and useful heat

[6, 7]. The approach is often utilized in active cooling systems to obtain simultaneous thermal and electrical energy output.

To increase the PV efficiency, several researchers focus their attention on the PVT collectors. The main components of typical water-based PVT collectors comprise the PV panels, absorber tubes, an insulated storage tank, and a tempered glass [8]. The air heat for industrial and domestic applications in the PVT system is analyzed using TRNSYS software. The industrial heat capacity of the system is determined after two distinct load supply temperatures. The solar thermal fraction produces relatively lower numbers, but the results show that polycrystalline PV cells have a greater efficiency than amorphous PV cells [9, 10]. An active cooling system installed on the PV module can increase the electrical efficiency by 7% with a water flow rate of 1 L/m [11].

The system electrical and thermal energy performance is analyzed using computer modeling as well as experiments conducted in the field, investigating how the water flow variations affect the PV electrical efficiency and solar collector thermal efficiency. The study findings show that greater water flow rate helps to reduce the PV temperature but can reduce the thermal efficiency. Therefore, the PVT system requires an appropriate water flow to optimize the generation of electricity and heat simultaneously [12]. Authors in [13] studied a zigzag thermal absorber PVT collector and spiral circular configuration. The use of a PVT system with a zigzag-shaped collector configuration was thermally and electrically 76.75% and 11.97% more efficient than without a cooling PV system. Meanwhile, the PVT system with a conventional spiral flow showed 54.8% thermal efficiency, and electrically the PV was 13.5% more efficient.

In [14], the electrical performance between three types of water-cooled PVT systems with mesh, direct, and spiral flow channel designs was studied and compared with ordinary PV systems. Each system's total efficiency was 7.8%, 18.5%, 28.0%, and 35.0%. The highest efficiency performance among the three water channel configurations was achieved by the spiral channel design. Based on a newly developed PVT, as the water flow increases at 180 L/h, the electrical efficiency becomes higher with the PV system producing more electrical power from 37.06 W to 140.48 W, while the increase of the electrical power from 38.45 W to 187.02 W is produced by the PVT-C system power [15]. In addition, the energy and exergy performances of three solar systems were compared and evaluated by numerical analysis using COMSOL Multiphysics [16]. The systems in question were a PV-S without cooling, a PVT-S partially cooled, and a fully cooled PVT-S. According to the findings, the fully cooled system provides the most efficient operation. When the system is partially cooled, the maximum TEF is 60.72%, and when the system is fully cooled, it reaches 70.89%. The improvement of EEF by 0.14% and 0.33% and TEF by 22.72% and 30.15% respectively, is achieved by increasing the mass flow rate from 0.0167 to 0.05 kg/s. Numerical simulations were conducted using the finite element method for 60, 90, 120, and 180 L/h of water to evaluate a hybrid Photovoltaic-Thermal System (PVT-S) against a traditional Photovoltaic Panel (PV-P) with a 70% polypropylene heat exchanger covering in El Jadida, Morocco [17]. The maximum power difference was 30.42 W between PVT-S and PV-P at a flow rate of 120 L/h. The average TEF of the PVT system ranged from 32.99% to 51.15%. In [18, 19], an updated PVT-S setup that is both lighter and simpler was proposed. The pressure drops, energy, and exergy performance were studied as a function of the fluid slick thickness and number of holes. Based on these findings, the reduction of the pressure drop by 109 Pa is achieved at the expense of a small increase in the cell temperature (0.3 °C) when the number of holes is increased from 10 to 60. Another study proposed a different PVT-S setup without the absorber plate, which would cut down on the weight, cost, and pressure drop by letting water contact the PV cell [20]. At its highest level, the system achieved an exergy efficiency of 16.51%, a TEF of 81.27%, and an electrical efficiency of 13.76%.

Based on the experimental results presented in [21, 22], the PVT solar collectors' performance is affected by various factors, including fluid flow, flow orientation in the pipe manifold, and geometric configuration of the collector. However, further studies are still needed, especially in the innovation of PVT collector design to optimize its electrical and thermal efficiency. The development of a water-based twin spiral PVT collector has not been studied yet. In this study, a new design of the PVT collector with a twin spiral configuration is investigated. The performance of the twin spiral configuration is evaluated under various water flow rates and solar energy intensities to assess its impact on both the electrical and thermal efficiency. An analysis of the PV module surface temperature distribution and the temperature of the collector outflow in steady-state conditions was carried out with a CFD-based simulation approach.

II. METHODOLOGY

A. *Model Geometry*

In this research, the modeled PVT system consists of PV modules combined with specially designed PVT collectors. The collector integrates the PV module with a rectangular pipe positioned at the back in a twin-spiral configuration, ensuring effective thermal management. Water is circulated through the collector, serving as the working fluid and acting as a medium for heat transfer. This process helps dissipate the excess heat and maintain a lower PV surface temperature, thereby improving the electrical performance and overall system efficiency. To evaluate the thermal behavior of the system, steady-state analyses were performed using ANSYS Fluent, focusing on both the PV surface temperature and the water outlet temperature from the collector.

The geometry of the twin-spiral configuration PVT collector is illustrated in Figure 1, while the individual layers of the PVT system are shown in Figure 2. The PV module used in this study has dimensions of 1080 mm × 680 mm. The collector is rectangular, with a thickness of 2 mm and a cross-sectional area of 15 mm × 15 mm. The total length of the collector channel is 15.2 m. A more detailed overview of the PVT system geometry adopted in the CFD analysis is provided in Table I. The accurate modeling of the PV module requires a clear understanding of its multilayer composition. Table II summarizes the thermophysical properties of each layer considered in the simulation [23]. It is important to note that the number and type of solar panel layers may vary depending on the manufacturer and production process. However, the values reported in the present study represent a widely accepted structure, ensuring a realistic representation of the PVT module within the CFD framework. However, the values reported in this work represent a widely accepted structure, ensuring a realistic representation of the module's physical behavior and enabling reliable predictions of the PVT system's thermal and electrical performance.

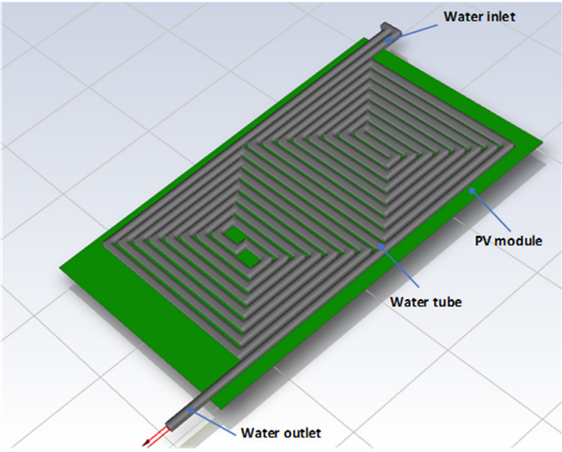
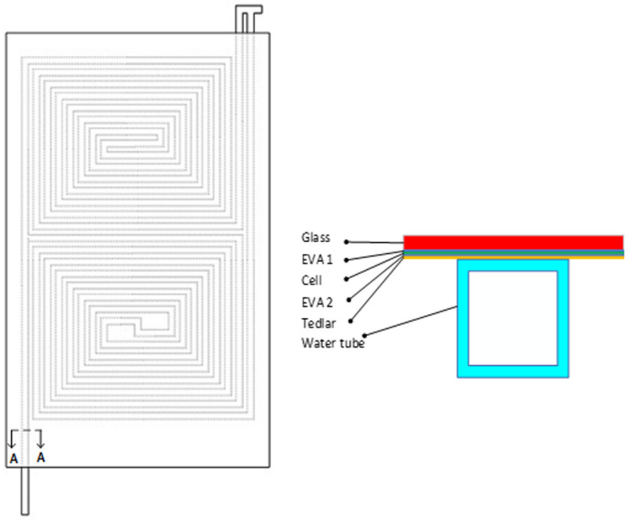


Fig. 1. Geometry of PVT collector with twin spiral configuration.



(a) (b)

Fig. 2. Layer of PVT system: (a) front view, (b) cross-sectional A-A.

TABLE I. GEOMETRIC DIMENSIONS OF PVT

Parameter	Dimensions (m)
Glass	1.02 x 0.68 x 0.003
EVA	1.02 x 0.68 x 0.0005
Solar cells	1.02 x 0.68 x 0.0003
Tedlar	1.02 x 0.68 x 0.0005
Aluminum	0.15 x 0.15x 0.002

B. Grid Independence Test

A grid independence test study was conducted to validate this simulation. The grid independence test was assessed by varying the grid size for the same geometry and comparing each result to ensure that the results were not affected by the grid size. Different grid sizes were used in the test, with a range of 10-4 mm grid. The comparison parameter chosen is the temperature module PV. The grid independence test is shown in Figure. 3. The graph demonstrates that the saturated results were achieved after 430,000 node counts. No discernible variation was found in the results beyond that threshold. Consequently, all geometries used in this work have a grid size of 5 mm.

TABLE II. PROPERTIES OF THE LAYERS PVT SYSTEM

Name	Thermal conductivity (W/m K)	Density (kg/m^3)	Heat capacity (J/Kg K)
Glass	2	3000	500
EVA	0.35	960	2090
Solar cells	148	2330	677
Tedlar	0.2	1200	1250
Aluminium	202.4	2719	871

C. Performance Evaluation

Thermal and electrical efficiency can be used to interpret the PVT system's performance [24]. There are numerous system design characteristics and operating variables that impact the PVT's thermal performance. This study analyzed the system at different variations of water flow and solar intensity. The solar collector TEF η_{th} is shown by [25]:

$$\eta_{th} = \frac{Q_u}{G\ A_c} \tag{1}$$

where Q_u represents the usable heat gain divided by the solar irradiance G and the PVT collector area A_c. The equation for the Qu is:

$$Q_u = \dot{m}\ C_p(T_o - T_i) \tag{2}$$

where C_p and $\dot{m}$ denote the water heat capacity and the mass flow rate, respectively. During simulation, T_o and T_i denote the water output and intake temperature, respectively.

The PVT system electrical efficiency is determined using [26]:

$$\eta_{el} = \eta_r\big(1 - \gamma(T_c - T_r)\big) \tag{3}$$

where T_r and T_c represent the reference temperature and the cell temperature, γ is the temperature coefficient (γ = 0,0041 °C^{-1}), η_r denotes the PV reference efficiency (η_r= 0,12), and η_{el} is the electrical efficiency PV.

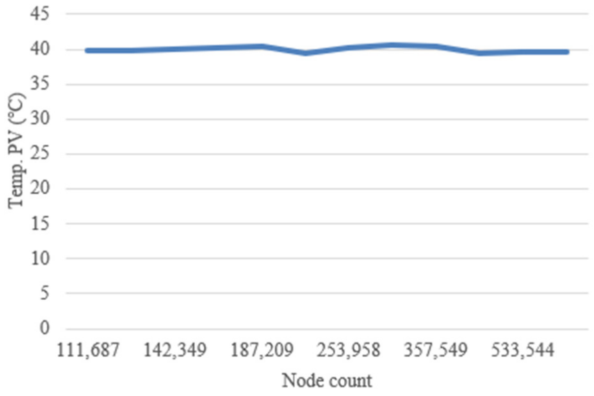


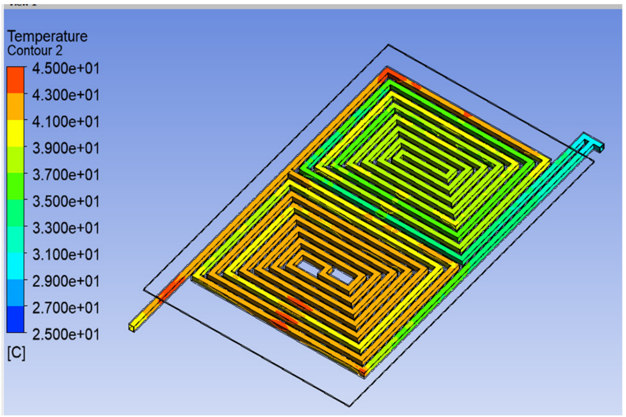
Fig. 3. Grid independence test.

III. RESULTS AND DISCUSSIONS

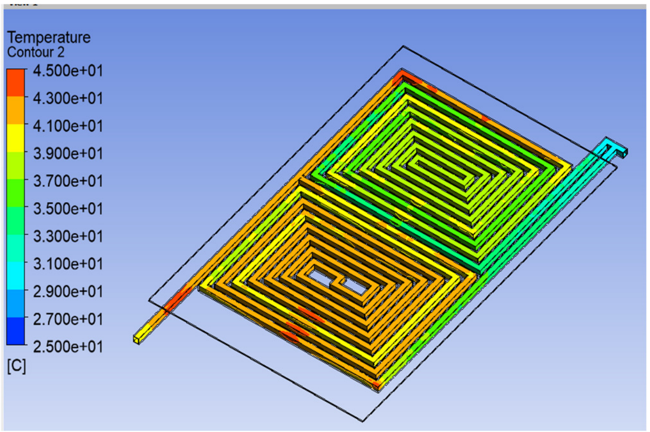
Research was carried out to determine the impact of the intensity of solar energy and water flow on the performance of planetary-driven twin spiral PVT collectors. The values of the solar irradiances: 500, 600, 800, and 1000 $\mathrm{W/m^2}$ were used for the simulations of PVT collectors. In the range of 0.01 kg/s-0.05 kg/s, the water flow was allowed to set. The experiment was conducted in a steady state environment, with the assumed absence of heat loss to the environment from the PV surface, while the water output temperature, as well as the electrical, thermal, and system efficiencies were determined by the water flow rate and solar irradiation level. In addition, varying the change settings can achieve optimal performance, serving as a valuable reference in the experimental approach and helping in designing practical research on water-based PVT technology in the field, particularly with twin spiral configuration.

A. *Temperature Distribution of PVT*

The simulation of the temperature distribution in the PVT system was conducted by comparing different mass flow rates under the same irradiance level and collector inlet water temperature. Figure 4 presents the results for a flow rate of 0.01 kg/s with an inlet temperature of 30 °C and solar irradiance of 800 W/m². Figure 5 displays the corresponding distribution when the mass flow rate was increased to 0.05 kg/s under the same conditions.

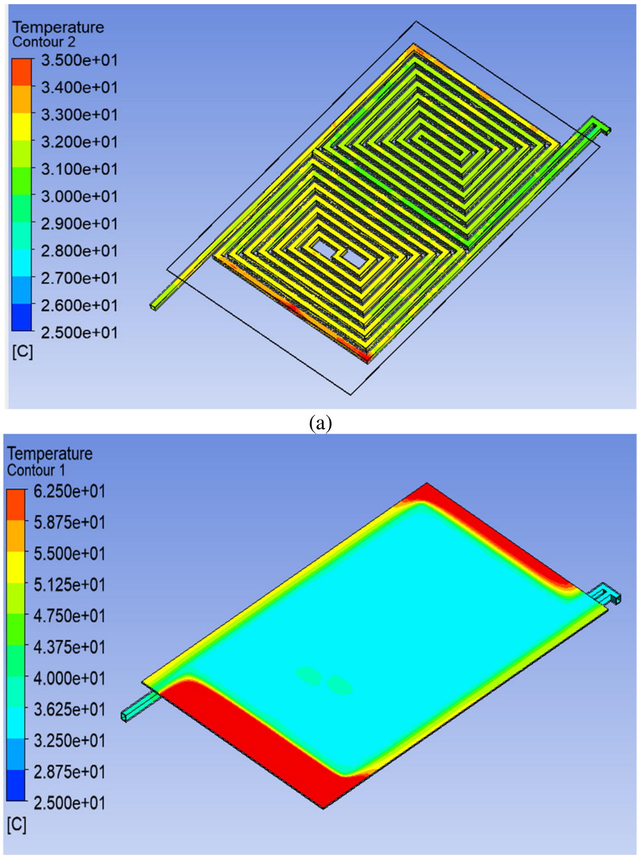


(a)



(b)

Fig. 4. Highest outlet temperature distribution with 800 $\mathrm{W/m}^{\wedge 2}$ and at a 0.01 kg/s: (a) collector PVT, (b) PV module surface.



(a)

(b)

Fig. 5. Highest outlet temperature distribution with 800 $\mathrm{W/m^2}$ and 0.05 kg/s: (a) collector PVT, (b) PV module surface.

In Figures 4(a) and 5(a), the temperature distribution on the surface of the PVT collector is presented. The analysis focuses on the variation of the water temperature along the collector channel and the effect of different mass flow rates on the outlet water temperature. When the mass flow rate was 0.01 kg/s, the water temperature increased from 30 °C to 40.52 °C, corresponding to a 35% rise. In contrast, at a higher flow rate of 0.05 kg/s, the outlet water temperature reached only 31.51

°C, which represents a 5.03% increase from the inlet temperature. These results indicate that a greater mass flow rate leads to a lower water outlet temperature compared to smaller flow rates.

Figures 4(b) and 5(b) illustrate the temperature distribution on the surface of the PV module. At a flow rate of 0.05 kg/s and a solar irradiance intensity of 800 W/m², the average PV module surface temperature was recorded at 36.88 °C. The surface areas directly adjacent to or in contact with the collector exhibited lower temperatures than the regions located further away. At the lower flow rate of 0.01 kg/s, the average module surface temperature rose to 44.48 °C. This demonstrates that a significant reduction in the PV surface temperature can be achieved by increasing the cooling water flow. Specifically, the results show a 17.08% decrease in the PV surface temperature when the flow rate was raised from 0.01 kg/s to 0.05 kg/s.

Several factors, including the solar irradiance intensity and water flow rate, influence both the average surface temperature of the PV module and the outlet water temperature of the collector. At the same irradiance level, an increase in the bulk flow rate results in lower PV and outlet water temperatures. This reduction contributes positively to the TEF and electrical efficiency of the PVT system, as maintaining lower module temperatures helps mitigate the efficiency losses caused by overheating.

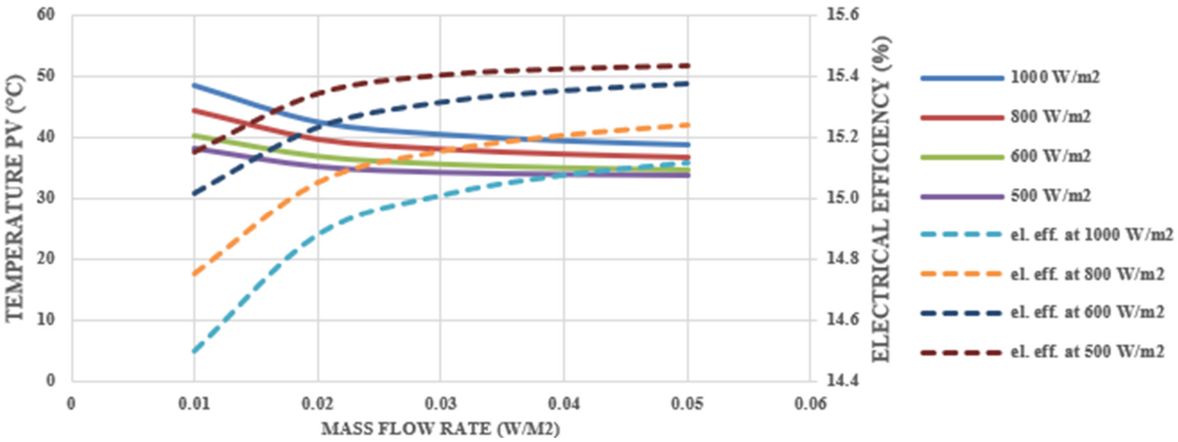


Fig. 6. Influence of different solar energy intensity and water flow rates on electrical efficiency.

B. *Electrical Efficiency under Varying Irradiance and Flow Rates*

ANSYS Fluent software was used to simulate the surface temperature of the PV module and the outlet water temperature of the collector. Different test cases were considered, where both the water flow rate and the solar irradiance intensity were varied to observe their influence on the system performance. To ensure reliability, the simulation results were cross-checked using the energy equation, which was then applied to estimate the electrical efficiency.

Figure 6 illustrates the effect of different irradiation levels and water flow rates on the power generation and surface temperature of the PV module. The simulations show that, at a solar irradiance of 800 W/m², increasing the water flow from 0.01 kg/s to 0.05 kg/s reduces the PV module temperature from 44.48 °C to 36.88 °C. This reduction in temperature leads to an improvement in the electrical efficiency, which rises from 14.75% to 15.24%. A similar trend was observed at other irradiance levels: higher water flow rates consistently lowered the module temperature and enhanced the electrical efficiency. These results confirm that maintaining a low module operating temperature by properly adjusting the coolant flow rate is essential for optimizing the performance of the PVT system.

Under favourable operating conditions, 500 W/m² solar irradiance and a water flow of 0.05 kg/s, the system achieved a maximum electrical efficiency of 15.43%. At this point, the PV module surface temperature was only 33.86 °C, which is comparatively low. On the other hand, the most critical condition occurred at 1000 W/m² irradiance with a low flow rate of 0.01 kg/s. In this case, the PV module temperature rose sharply to 48.47 °C, causing the electrical efficiency to drop to its minimum value of 14.5%. This finding highlights the importance of a higher coolant flow rate in controlling the module temperature, ensuring that the electrical performance of the PVT system remains stable even under high irradiance.

Overall, when the flow rate is kept constant, an increase in irradiance results in higher PV temperatures and reduced electrical efficiency. Conversely, at a given irradiance level, increasing the mass flow rate effectively lowers the module temperature and improves efficiency.

C. *Thermal Efficiency under Different Irradiance and Flow Conditions*

The TEF and water temperature at the collector's outflow are two of the metrics used to assess the PVT system's thermal performance. Figure 7 depicts the correlation between the changes in the water flow and the level of solar irradiance concerning these two parameters. Generally, while boosting the water flow does improve TEF, it also lowers the water's temperature at the collector's output. This phenomenon occurs because the faster flowing fluid is able to absorb heat more effectively without experiencing a too high a temperature rise. Raising the water flow rate from 0.01 kg/s to 0.05 kg/s improved TEF from 77.95% to 80.76% when exposed to 800 W/m² of solar energy intensity. Under these circumstances, the water temperature at the collector's output dropped from 40.52°C to 31.51°C. To improve the heat transfer and TEF in PVT systems, especially under high irradiation circumstances, the findings show that controlling the mass flow rate is critical.

The PVT system yielded a collector water output temperature of 32.3 °C when the water flow was adjusted at 0.05 kg/s and the solar energy intensity reached 1000 W/m². This helped achieve the greatest TEF of 81.55%. In contrast, the system attained its lowest TEF of 74.22% when it was operated at 0.01 kg/s water flow and 500 W/m² solar energy intensity. Under these conditions, the output water temperature increased to 44.04°C. A comparison of these two scenarios shows that an increase in the water flow rate results in a reduction of the water temperature at the collector output, signifying that heat transfer occurs more efficiently as the fluid transports greater energy without a substantial rise in temperature. Thus, TEF is enhanced, and the water temperature of the output collector is reduced as the fluid flow rate increases, especially when the system receives high intensity solar irradiance. This simulation was conducted under steady-state conditions, so transient time variations were not considered. Furthermore, the solar energy intensity is modeled as a constant value uniformly distributed over the PV surface, without accounting for the solar angle variation or partial shading, and the fluid flow is assumed to be turbulent and uniform.

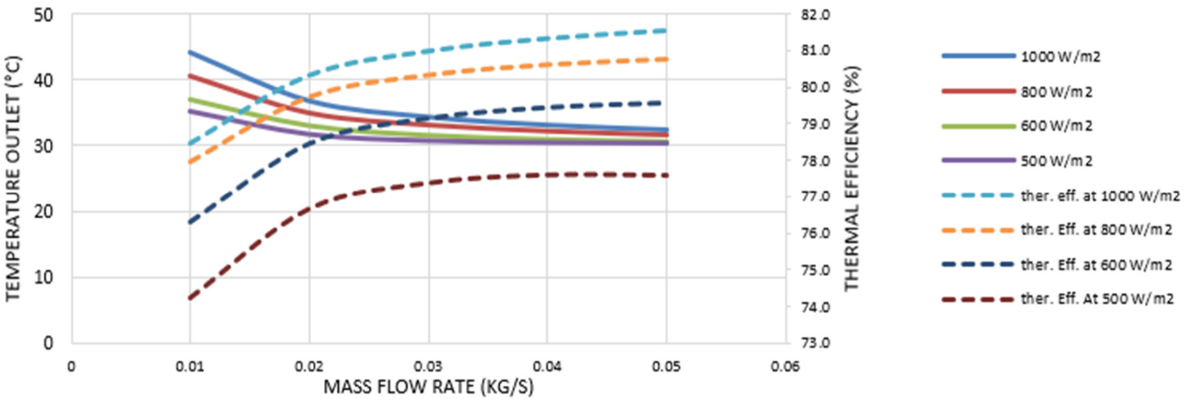


Fig. 7. Influence of different solar energy intensity and water flow rates on thermal efficiency.

TABLE III. WATER-BASED PVT COLLECTOR COMPARISON

Design collector	**Reference**	**Electrical Efficiency (%)**	**TEF (%)**	**Remark**
Serpentine tube	[28]	-	58	The collector inlet water temperature stabilized at 37.7 °C, while the average collector outlet temperature reached 58 °C.
Spiral flow absorber	[29]	13.8	54.6	The total system PVT efficiency reached 68.4%.
Twisted absorber tubes	[30]	9.4	75.2	The PV panel temperature decreased from 73.41°C to 65.5°C.
Serpentine tube with nano fluid	[31]	17.61	71.17	Unglazed PVT using nano fluid cooling medium. The panel temperature decreaed by 23.7°C at noontime (68.4°C).
Innovative cooling box design	[27]	17.79	76.13	Utilizing nano fluid as the operating fluid. The inlet water temperature of the collector was 15 °C.
Roll-bond thermal absorber	[32]	14.5	-	Demonstrated uneven flow distribution but improved electrical efficiency.

D. Comparison of PVT Collector with Previous Studies

The achievement of the current research is compared with that of earlier research in this section. The present investigation examines the performance of the water-based PVT collector with a twin spiral configuration, which generates electrical efficiency ranging from 14.5% - 15.4% and TEF from 76.3% - 81.75%. Table III displays the results of previous research conducted on the performance of the water-based PVT collector.

Water-based PVT collectors exhibit varied performance based on their design and operational conditions. The innovative cooling box design shows the highest TEF, while twin spiral configuration achieves the highest electrical efficiency [27]. The optimal performance is greatly reliant on several elements, including the water flow rate, solar energy intensity radiation, and the collector configuration.

IV. CONCLUSIONS

An investigation on twin spiral configuration water-based PVT collectors has been conducted. Several mass flow rate and solar radiation level variations were carried out to evaluate the PVT efficiency. With a fixed 800 W/m² solar energy intensity and 0.01 kg/s water flow, the temperature of the water discarding the collector rosed from 30°C to 40.52°C, a 35% increase. Under these circumstances, a temperature of 36.88 °C was attained on average for the PV modules. As a counterpoint, increasing the water flow to 0.05 kg/s raises the average temperature of the PV modules to 36.88°C, while the temperature at which water exits the collector only rises to 31.51°C, an increase of around 5.03%. These results show that the collector outlet water temperature tends to be lower as the mass flow rate becomes greater, which has an impact on the lower PV module average temperature. On the other hand, a lower mass flow rate has a greater effect on the average temperature of the PV modules, since it causes the water at the collector's output to be warmer. The PV module achieved the highest electrical efficiency of 15.43% at a water flow rate of 0.05 kg/s and 500 W/m² solar energy intensity, with an average temperature of 33.86°C. The minimum efficiency was 14.5% when exposed to 1000 W/m² radiation and a water flow rate of 0.01 kg/s. The system reached its peak Thermal Efficiency (TEF) of 81.55% at a water flow rate of 0.05 kg/s and 1000 W/m² radiation intensity, with an output water temperature of 32.3°C. The findings show that the thermal and electrical performance are significantly affected by the ratio of the solar energy intensity to the water flow rate. Further studies can be conducted using alternative cooling fluids, such as nanofluids, Phase Change Material (PCM), or hybrid fluids.

ACKNOWLEDGMENT

This research was funded by a grant from the National Research and Innovation Agency, Indonesia (Rumah Program OREM No. 7/III.3/HK/2025).

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