Journal of Heat and Mass Transfer Research

Journal homepage: https://jhmtr.semnan.ac.ir

Semnan University

ISSN: 2383-3068

Research Article

Experimental Evaluation of the Hybrid-Bifacial Cooling of a PV Panel in Arid Weather Using Channel Heat Exchanger and Impingement Flow Nozzles

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A R T I C L E I N F O

Article history:

Received: 2023-11-04

Revised: 2024-04-08

Accepted: 2024-04-09

Keywords:

Electrical and thermal efficiency;

Jet impingement;

Photovoltaic-thermal panel;

Air-water hybrid cooling;

Coefficient of energy.

A B S T R A C T

In the current global energy conditions, with a growing concern for carbon emissions, the adoption of renewable energy sources is on the rise. Solar panels have emerged as a highly promising method for electrical-thermal energy generation and are widely employed in both industrial and residential settings. This study focuses on evaluating the impact of cooling on PV panel systems and its effect on electrical and thermal efficiency. A hybrid method utilizing both air and water on the PV panels is examined, and the results are compared to those of a reference panel. The experiments were conducted in Kashan, Iran, located at coordinates 34°06' N 51°23' E, in July 2023. By implementing the proposed cooling method, significant improvements in the maximum daily electrical, thermal, and total efficiencies can be achieved, surpassing 20%, 30%, and 50%, respectively. The findings indicate that cooling with water proves more advantageous in terms of thermal energy generation, although it slightly decreases the coefficient of energy due to the additional energy required for water pumping compared to air blowing. Furthermore, the study reveals that bifacial cooling, employing jets to cool both sides of the PV panel, significantly enhances thermal and electrical efficiency, particularly in hot and dry weather conditions.

1. Introduction

In recent years, the demand for renewable energy sources has significantly increased due to the growing awareness of environmental sustainability and the need to reduce reliance on non-renewable fossil fuels [1,2]. Among the various renewable energy technologies available, photovoltaic (PV) systems hold great promise for harnessing solar energy to generate electricity [3,4]. However, as the efficiency of PV panels is intrinsically linked to their operating temperature, ensuring effective cooling becomes essential to optimizing power generation. The continuous exposure of PV panels to sunlight leads to the absorption of solar radiation, resulting in the conversion of this energy into electricity. However, the conversion process is not entirely efficient, and a significant portion of the absorbed energy is dissipated as heat [5,6]. Elevated panel temperatures can detrimentally affect the performance and lifespan of PV systems, causing a decline in their electrical output and overall efficiency. Therefore, mitigating the adverse effects of excessive heat through effective cooling techniques is crucial for maximizing power generation and ensuring the long-term viability of PV installations. These efforts make the panels called PV thermal panels

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Cite this article as:
Balal, A., Sheikhzadeh, G.A. and Fattahi, A., 2024. Experimental Evaluation of the Hybrid-Bifacial Cooling of a PV Panel in Arid Weather Using Channel Heat Exchanger and Impingement Flow Nozzles. *Journal of Heat and Mass Transfer Research*, 11(2), pp. 195-210.
https://doi.org/10.22075/JHMTR.2024.32229.1495

(PVT) if the thermal energy is also utilized [7,8]. The importance of efficient cooling strategies for PV panels has been the subject of extensive research and active or passive technological advancements based on air or liquid coolants.

Sweelem et al. [9] conducted a study on the effect of submerging PV panels in water. Their findings indicated a decrease in panel temperature from 70°C to 30°C, resulting in a 2.5% increase in efficiency. At a depth of 4cm, the efficiency reached a value of 15.5%. However, they noted that increasing the depth led to undesirable results due to the mirror effect. The authors also highlighted the positive influence of air on improving panel efficiency. In a separate study, Krauter [10] observed higher efficiency in a water-cooled PV panel. They emphasized the significant contribution of maintaining a clean surface on power generation, noting that efficiency could increase by approximately 30% with regular dust cleaning. Fang et al. [11] reported a substantial improvement in system efficiency when reducing panel temperature from 52°C to 8°C, while the cooling water temperature increased from 20°C to 42°C. The efficiency increased from 9.4% to 10.9%.

Wu et al. [12] conducted a study on the cooling of an integrated PV system and found that the use of heat pipes could accelerate the cooling process. They observed that increasing the heat loss coefficient improved the electrical efficiency while applying colder inlet water and increasing the mass flow rate enhanced the total thermal efficiency. The achieved efficiencies were 63.65% and 8.45% for electrical and total thermal efficiency, respectively. Kumar et al. [13] investigated the impact of various parameters, including radiation intensity and air mass flow rate, on panel efficiency. They found that an increase in the air mass flow rate had a negative influence on efficiency, while an increase in radiation intensity had a positive influence. Additionally, attaching fins to the panels was studied, and it was demonstrated that this approach could improve thermal and electrical efficiency by 15% and 10.5%, respectively. In terms of passive cooling features, Hernandez et al. [14] showed that maintaining a constant coolant mass flow rate led to a modest improvement of 1.25% in efficiency.

Moharram et al. [15] conducted a study using six 185-watt panels equipped with 120 water nozzles to develop a cooling system with minimal energy and water consumption. By maintaining the panels' temperature at 45°C, they observed a temperature decrease of approximately 10°C and a 12.5% increase in efficiency when the cooling system operated for 10 minutes. Bahaidarah et al. [16] investigated the double-facial cooling of PV panels. They observed that the front and rear temperatures decreased to 35°C and 25.9°C, respectively, from their initial values of 45°C and 42.8°C. This cooling approach resulted in an approximately 10% increase in efficiency. Teo et al. [17] conducted a comparison between air and water as coolants for PV panels and concluded that water was more efficient. By employing aiding fins in the cooling channel, water demonstrated a 2% higher efficiency compared to air-cooling. A similar study performed by Nizetic et al. [18] reported an efficiency of 16.3% using water as a coolant.

Noghrehabadi et al. [19] conducted an experimental investigation to analyze the effect of different volumetric flow rates on the efficiency of a stationary solar collector with a conical geometry. They tested various flow rate values ranging from 0.35 to 2.8 L/min. The results demonstrated a significant improvement in collector efficiency as the flow rate increased. The unique conical shape of the collector facilitated the absorption of all parts of solar radiation, and the flow centrifugal forces generated by longitudinal vortices contributed to the enhancement of efficiency. Nahar et al. [20] conducted a study that showed increasing the airflow in the cooling channel from 0.0003 to 0.0007 m/s resulted in an efficiency improvement to the value of 20%.

Wu et al. [21] introduced a cooling system for solar panels that involved attaching a water channel to the panel. They considered parameters such as mass flow rate, inlet coolant temperature, channel height, and solar radiance intensity. The efficiency of their cooling system was found to be higher compared to systems using conventional cooling methods. Despite the decrease in power generation due to the presence of water on the panels, the overall efficiency increased. In another study, the cooling of the front panel surface was examined with and without water spray. It was observed that applying water sprays resulted in higher efficiency, with efficiency values of 16.2% and 13.7% [22]. Chin et al. [23] used multiple parallel channels with a dimension of 15mm to cool down the temperature of the solar panel by 21°C. This cooling approach led to improvements in both electrical and thermal efficiency, with a 2% increase in electrical efficiency and an 8% increase in thermal efficiency.

Panda et al. [24] compared the front and back surface cooling of PV panels. They found that the temperature of the PV panel had a significant impact on performance, efficiency, and longevity. By applying water flow and wetting the front and back surfaces of the panel, they were able to decrease the panel temperature by more than 21°C. This resulted in a power generation increase of more than 28%. The study concluded that cooling the front surface of the panel had a more significant impact on energy production compared to cooling the back surface, which only improved efficiency by about 1%. With an 8°C reduction in panel temperature, the efficiency was enhanced by approximately 30%. Khalaf et al. [25] examined a PV panel cooling using an active cooling open water cycle in Samarra, Iraq. The results showed significant improvements, including a 69.4% increase in electrical power and maximum daily efficiencies of 10.2% (electrical), 82.3% (thermal), and 92.5% (overall). The study demonstrated the effectiveness of the active cooling system in mitigating the hot climate's challenges.

Rejeb et al. [26] designed a thermal photovoltaic collector that incorporated an anti-reflective coating, a low emissivity coating, and a heat exchanger to minimize heat loss between the cooling fluid (water) and the solar cells. The introduction of these features resulted in increased electrical and thermal efficiencies for the system. Specifically, the electrical efficiency improved from 13.7% to 15.4%, while the thermal efficiency increased from 58% to 73%. Meyer and Busiso [27] conducted a comparative study between natural and forced water convection cooling for a photovoltaic (PV) system. They found that the thermosiphon effect, driven by natural convection, was dominant in the cooling process. The ambient temperature was varied between 15 to 28°C from 7 AM to 6 PM. The study showed that forced convection cooling resulted in a panel temperature of 34°C, while natural convection cooling led to a higher panel temperature of 58.64°C. As a result, the electrical efficiency experienced a maximum increment of 3.63%. Lin et al. [28] conducted an experimental study on an air-based photovoltaic-thermal (PVT) system that incorporated a concentric phase change material (PCM) with different slopes and configurations. They used a statistical method to identify the deficiencies of the system and determine the optimal design. The overall efficiency of the system increased from 37.6% to 40.2% on average, compared to a reference case. A similar study was conducted by Carmona et al. [29] to compare the testify panel with those equipped with cooling fluid flow and a PCM. The daily electrical efficiency was raised by about 0.5% and the total capacity to extract useful energy increased by about 20%.

Herrando et al. [30] examined a PVT used for cooling using an absorption chiller. The reference cases for comparison were an evacuation tube for heating and cooling as well as a PV for electricity generation. The system had the potential to displace 911 tons CO_2 per year; however, the payback time of the current system compared to the reference cases was considerably high. Karami et al. [31] studied the thermal performance of the solar polygeneration system integrating PVT collectors with hybrid HDH/RO units in hot and dry climate zones. They found that by increasing the PV cell temperature, the collector's electrical and thermal efficiency decreased to its minimum value at the maximum cell temperature between 12:30 and 1:30 PM. The maximum and minimum total PVT efficiencies were respectively 62.8% at 1:30 PM and 70.3% at 4:00 PM. The maximum and minimum electricity generation occurred in October and February, which are 863 kWh and 428.7 kWh, respectively.

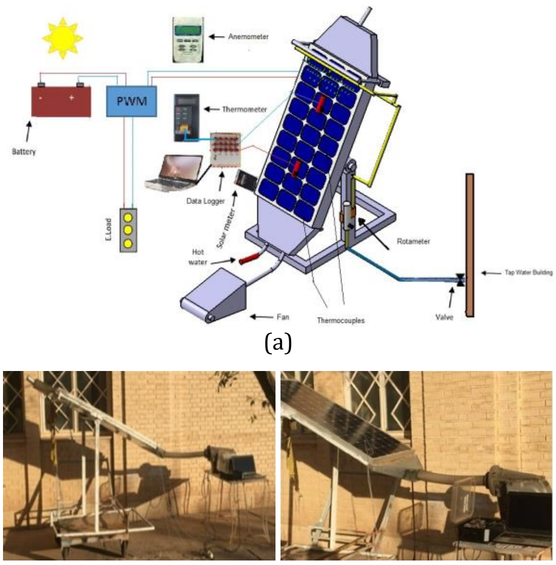
The application of nanofluid for cooling the PV panels is also the subject of some investigations, stemming from the desirable heat-transferring characteristics of nanoparticles. Arifin et al. [32] investigated the use of TiO_2 nanofluids as a cooling fluid in a PV unit. Through experimental and numerical analysis, they found that employing TiO_2 nanofluids as the cooling fluid resulted in an increase in PV efficiency to 13.04%. Diwania et al. [33] conducted a study to evaluate the performance of a hybrid PVT system utilizing Cu/water and Al_2O_3/water as nanofluids. The results showed that the Cu/water nanofluid exhibited superior performance compared to the Al_2O_3/water nanofluid in the hybrid PV unit. Furthermore, the study reported a significant enhancement in thermal efficiency of 4.45% when using the Cu nanoparticles, as compared to the base fluid. Salehi et al. [34] conducted experimental investigations to assess the impact of aluminum nanoparticles on the cooling performance and conversion efficiency of PV panels. The study took place in Mashhad, Iran, on a sunny winter day in November with ambient temperatures ranging from 10 to 17 °C. The experimental findings demonstrated that the use of a nanofluid containing aluminum nanoparticles resulted in an average improvement of 13.5% in solar panel efficiency and a 13.7% increase in the output power of the PV panels, as compared to water cooling without aluminum nanoparticles. Additionally, the application of the nanofluid with aluminum nanoparticles led to a temperature reduction ranging from 13.08 to 16.34 °C on the surface of the solar PV panels when using a heatsink cooling system. In conclusion, the results indicate that the addition of aluminum nanoparticles to the nanofluid effectively enhances the conversion efficiency of PV panels.

This work presents an experimental analysis of cooling flows tailored for PV panels, with a primary focus on their potential to enhance efficiency. A comprehensive review of the existing literature underscores the critical need for innovative cooling strategies in the field of PV panels. Although PV cooling has been studied yet, more investigations, especially those upon hybrid methods still need to be developed. Motivated by the imperative to enhance the performance of PV systems, this research examines the technical details of hybrid cooling methods, by implementing it on both the front and back surfaces of the panels and applying water and air. By investigating the influence of parameters, such as flow rate and coolant type, the present work aims to uncover critical insights into the determinants of cooling effectiveness. The envisioned impact of this work extends beyond the laboratory, contributing substantively to the development of environmentally friendly, economically viable, and scalable cooling solutions for PVs.

2. Research Methodology

2.1. Test Rig Facility and Instrumentation

Fig. 1(a) illustrates the schematic view of the test rig that was constructed and utilized for this study. The setup was situated on the rooftop of the Energy Institute of the University of Kashan, located in Kashan city, at an elevation of 1000 m above sea level. The experiments were conducted during the arid and hot summer weather. Real images of the test rig are also presented in Fig. 1(b).



(a)

(b)

Fig. 1. (a) The schematic view and (b) The real figure of the setup manufactured

The dimensions of the setup were 110 cm in width and 225 cm in length. Two identical PV panels were employed, one for the control case without cooling and the other for evaluating different cooling methods, both with a rated power of 190W. The details of the PV panel applied in the current experiments, manufactured by Faran Electronics Industries, are presented in Table 1.

Table 1. The features of the PV panel applied

Feature	Value
Maximum power (W)	190
Open circuit voltage(V)	44.8
Short circuit current (A)	5.7 8
Nominal operating cell temperature (°C)	45±3
Cell technology	MONO-Si
Dimensions (mm)	1580* 808*40

The setup incorporated features that facilitated cooling, either with air or water as the coolant. To achieve this, a centrifugal pump was used for water circulation, while a blower was employed for air cooling. Additionally, the setup was equipped with three water nozzles for generating fog on the front surface. To control the mass flow rate, a valve was employed, and the flow rates of air and water were measured using two separate rotameters. The panel slope was fixed at 34 degrees relative to the horizon, determined based on the site's coordinates (34°06' N 51°23' E). The experiment was conducted in July 2023. Temperature was measured using PT100 resistance thermometers, with two sensors placed at the inlet and outlet of the cooling flow. These sensors recorded the temperature data, which was then logged using an eight-channel data logger. Furthermore, two additional PT100 resistance thermometers were mounted on the 25% top and bottom of the panel to measure the surface temperature. To shield these sensors from direct sunlight radiation, a cover was utilized. The sunlight intensity in each test case was measured using a solar power meter (Pyranometer). Additionally, a solar charge controller was used to measure the voltage and current produced by the PV panel.

To ensure the working of the charge controller, a closed electrical circuit with a consumer was required. Therefore, a 9A battery and a 15W LED were connected as part of the circuit. The ambient temperature and relative humidity were recorded throughout the experiments, ranging from 34 to 45°C and 10 to 15%, respectively. As it is crucial, the variations of the ambient temperature and environmental humidity are described in Fig. 2 on average for Kashan during the second half of July 2023 when the experiments were conducted. Wind speed measurements were obtained using an anemometer, which varied from 0.5 to 1.3 m/s. The sampling data period for the current study was set at 30 minutes, spanning from 9 AM to 4 PM. However, to reduce random errors, each data point was recorded as an average of 10 individual samples. For a comprehensive overview of the instruments used in the experiments, refer to Table 2, which provides detailed information on the instrument specifications and configurations utilized in the current study.

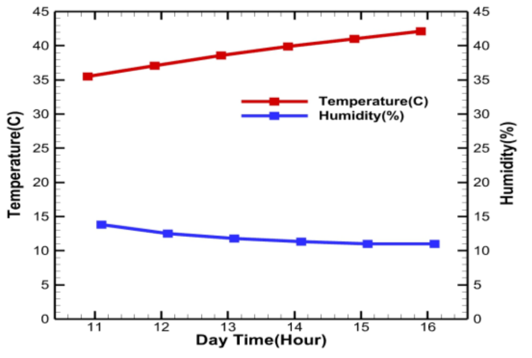
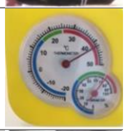


Fig. 2. Average variations of the ambient temperatue and humidity of tests location during the second half of July 2023 igure

Table 2. Details of the used instruments

Instrument	Working range	Brand	Error	Figure
Solar power meter	400-1100nm (spectral response)	TES-1333	±5%	
Resistance thermometer	-200C to +850C	JUMO	0.12C (Maximum)	
Rotameter	1 to 8 lit/s (water) 19 to 40 m3/s (air)	ZYIA instrumentation company	3.5% (Maximum)	
Data logger	-	Homemade	±5%	
Relative humidity transmitter	0 to 100%	HTC	±5% (for RH of 10-90%)	
Digital anemometer	0.4 to 30m/s	LUTRON (YK-2005AM)	2.0% (Maximum)	
Solar Charge controller	PV input power: 520W for 12V battery system, 1040W for 24V battery system	EPEVER (VS1024A)	1% (Maximum)	

2.2. Performance Indicator

To evaluate the mean electrical efficiency of the PV panel ($\eta_{elec,mean}$), the net electrical power gained from the system in the whole time sampling is divided into the sunlight power received, as [35]

$$\eta_{elec} = \frac{\dot{E}_{elec}}{\dot{E}_{sun}} = \frac{P_{PV} - P_{pumping}}{A_{PV}\ G_t} \times 100\%, \qquad (1)$$

in which P_{PV} means the electrical energy produced, A_{PV} indicates the panel's active surface area, $G_{t,i}$ denotes the radiation heat flux received and $P_{pumping}$ addresses the electrical power required for pumping the cooling fluid flow. Considering the PV panel as a thermal-electrical system, one can define the mean thermal efficiency ($\eta_{th,mean}$) using the thermal energy that the cooling flow receives [35].

$$\eta_{th} = \frac{\dot{E}_{th}}{\dot{E}_{sun}} = \frac{\dot{Q}_{PVT}}{A_{PVT}\ G_t} \times 100\%, \qquad (2)$$

$\dot{Q}_{PVT}$ signifies the heat transfer to the cooling fluid flow by the PV panel and is defined by [36]

$$\dot{Q}_{PVT} = \rho \dot{V} c_p (T_{out} - T_{in}), \qquad (3)$$

where ρ, $\dot{V}$ and c_p illustrates respectively the density, flow volume rate and specific thermal capacity of the cooling fluid flow. T_{out} and T_{in} respectively indicates the outlet and inlet temperature of the cooling flow. The energy balance of the studied PV is formed by the solar power input ($\dot{E}_{sun}$), electrical ($\dot{E}_{elec}$) and thermal output power ($\dot{E}_{th}$) and losses ($\dot{E}_{losses}$), as

$$\dot{E}_{sun} = \dot{E}_{elec} + \dot{E}_{th} + \dot{E}_{losses}. \qquad (4)$$

The losses in a PV panel include

- Conversion Losses: These losses occur during the conversion of solar energy into electrical energy and are primarily attributed to the inherent inefficiencies of the PV cells and associated electronics.
- Reflection and Transmission Losses: Some of the incoming solar energy is reflected or transmitted through the panel without being absorbed, resulting in energy losses.
- Wiring and Connection Losses: Resistance in the electrical wiring and interconnections within the PV system can cause energy losses.
- Temperature-Related Losses: PV panels can experience a decrease in performance as their temperature rises. This is known as the temperature coefficient and can

result in a reduction in overall energy output.

- Soiling and Shading Losses: When the surface of the PV panel is dirty or partially shaded, the amount of solar energy reaching the solar cells is reduced, leading to energy losses.

The current study tries to decrease the temperature-rated losses as well as increase the thermal energy harvesting. Using the energy balance, the mean total efficiency by considering the whole energy captured from the panel is calculated by

$$\eta_{total,mean} = \frac{\dot{E}_{elec}}{\dot{E}_{sun}} + \frac{\dot{E}_{th}}{\dot{E}_{sun}} = \frac{P_{PV} - P_{pumping} + \dot{Q}_{PVT}}{A_{PVT}\ G_t} \times 100\%, \quad (5)$$

To compare the cooled and uncooled PV, a parameter called coefficient of energy (COE) is used, indicating the net energy generation of the cooled PV on the uncooled energy as [37]

$$COE = \frac{P_{PV,cooled} - P_{pumping}}{P_{PV,uncooled}}. \quad (6)$$

2.3. Uncertainty Analysis

The uncertainty in experimental result analysis is essential to find the validity of the captured data. There are two sources of uncertainty; random and bias errors. The former is tried to be reduced by measuring a parameter ten times and averaging the data captured. The latter is determined by the error of the instruments applied in the current study earlier shown in Table 2. The uncertainty of the useful thermal energy, sunlight energy, and thermal and electrical efficiency is respectively given by [38-40]

$$\frac{\Delta\dot{E}_{th}}{\dot{E}_{th}} = [\left(\frac{\Delta\dot{m}}{\dot{m}}\right)^2 + \left(\frac{\Delta T_{in}}{T_{in}}\right)^2 + \left(\frac{\Delta T_{out}}{T_{out}}\right)^2]^{0.5}, \quad (7)$$

$$\frac{\Delta\dot{E}_{sun}}{\dot{E}_{sun}} = [\left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta I}{I}\right)^2]^{0.5}, \quad (8)$$

$$\frac{\Delta\eta_{th}}{\eta_{th}} = [\left(\frac{\Delta\dot{E}_{sun}}{\dot{E}_{sun}}\right)^2 + \left(\frac{\Delta\dot{E}_{th}}{\dot{E}_{th}}\right)^2]^{0.5}, \quad (9)$$

$$\frac{\Delta\eta_{elec}}{\eta_{elec}} = [\left(\frac{\Delta\dot{E}_{sun}}{\dot{E}_{sun}}\right)^2 + \left(\frac{\Delta I_{SC}}{I_{SC}}\right)^2 + \left(\frac{\Delta V_{OC}}{V_{OC}}\right)^2]^{0.5}. \quad (10)$$

in the last equation, I_{SC} and V_{OC} indicates the short circuit current and open circuit voltage, respectively. The uncertainty depends on the error as well as the absolute parameter values. Therefore, the uncertainty depends on each sample data. However, the maximum uncertainty values for thermal and electrical efficiency are respectively calculated as 2.1 and 3.6 percent.

3. Results and Discussion

The experiment was conducted in various cases. The cooling of the PV was performed on the top or bottom surface of the PV using air or water, as presented in Table 3. The airflow was provided by a blower, while the water flow was fed by the water pipeline. Table 3 provides the cooling using air, water, or hybrid cooling. The values selected for the mass flow rate of the coolants depend on the limitations of the equipment and measuring tools, as well as the energy consumption associated with pumping and the need to ensure sufficient heat removal. Using various mass flow rates allows for meaningful comparisons, as it serves as an independent parameter for analysis.

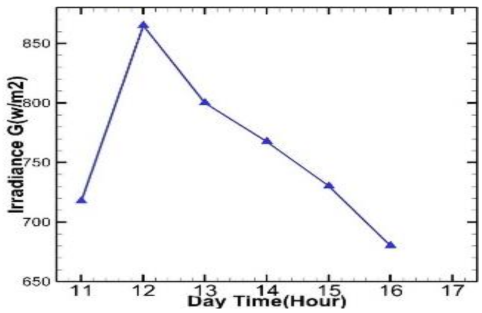
A channel heat exchanger at the bottom and/or water jets on the panel surface are examined. As described earlier, the thermal energy received by the cooling fluid, as well as three types of efficiency and COE are evaluated. The inlet temperature of the air or water coolant is approximately the ambient temperature. The outlet temperature of the air and water was (3.3-11.5) °C and (2.1-6.5) °C higher than the inlet temperature, respectively. Before cooling, the PV panel temperature fell in the range of (51-88) °C, but it reduced to the range of (32.5-52) °C after the cooling process.

In Fig. 3a and b, the relationship between global solar irradiance, G (W/m2), and electrical efficiency is respectively depicted for the testimonial case (Case 1), representing the uncooled PV system. The electrical efficiency in Case 1 is anticipated to exhibit the lowest values compared to the other cooled cases. This assessment is particularly relevant during daytime when solar irradiance reaches considerable levels. It is essential to note that changes in solar radiation can lead to variations in solar power received and, subsequently, impact electrical efficiency. However, the magnitude of these changes depends upon factors such as the type of PV panels, the cleanliness of the panel surfaces, and the geographical latitude.

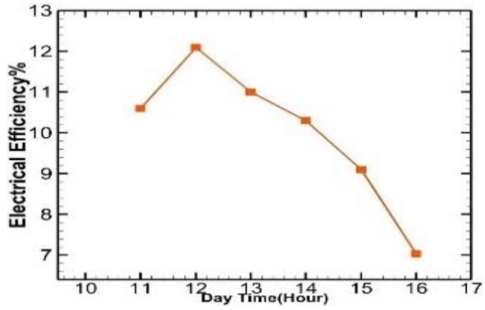
Table 3. The test case description in the current study

Case		Description
	1	No cooling.
Air cooling	2	Airflow in the bottom channel with $\dot{m} = 0.024kg/s$.
	3	Airflow in the bottom channel with $\dot{m} = 0.043kg/s$.
	4	Airflow in the bottom channel with $\dot{m} = 0.061kg/s$.
Water cooling	5	Water flow in the bottom channel with $Q = 0.5L/min$.
	6	Water flow in the bottom channel with $Q = 1.5L/min$.
	7	Water flow in the bottom channel with $Q = 2.5L/min$.
	8	Water jets on PV with $Q = 1.5L/min$
Hybrid cooling	9	Water jets on PV with $Q = 1.5L/min$ and airflow in the bottom channel with $\dot{m} = 0.061kg/s$.
	10	Water jets on PV with $Q = 1.5L/min$ and water flow in the bottom channel with $Q = 2.5L/min$.

As Fig. 3b indicates, during the daytime, as solar irradiance varies, the electrical efficiency experiences fluctuations. In the afternoon, a discernible decrease in electrical efficiency, approximately 5 percent, is observed. This reduction is attributed to the changing dynamics of solar radiation during the day. The observed trend in electrical efficiency closely follows the pattern presented by solar irradiance. This alignment is indicative of the direct impact of solar radiation on the electrical efficiency of the uncooled PV system.



(a)



(b)

Fig. 3. (a) The global solar irradiance and (b) electrical efficiency for the testimonial case

Fig. 4 illustrates the thermal energy received by the air coolant for Cases 2 to 4. The increase in air mass flow rate within the bottom channel leads to a proportional rise in thermal energy received. Specifically, as the air mass flow rate (ṁ) intensifies from 0.024 to 0.043 kg/s and from 0.043 to 0.061 kg/s, the thermal energy received increases by 17% and 27%, respectively. This correlation underscores the influence of air mass flow rate on the efficiency of thermal energy absorption by the cooling system. Notably, the graphical trend mirrors that of solar irradiance (Fig. 3a), reaching its maximum around noon. The synchronicity between solar irradiance and thermal energy received by the air coolant emphasizes the dependence of the cooling system on solar radiation dynamics.

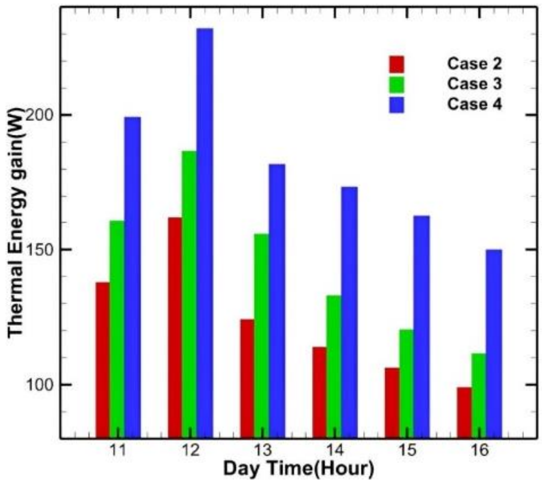


Fig. 4. The thermal energy gained for case 2, case 3, and case 4

Moving to Fig. 5, which presents the thermal energy received for Cases 5 to 8 with water coolant, a distinct performance improvement is evident compared to the air-cooled cases. The application of water flow in the bottom channel (Cases 5 to 7) results in an average cooling improvement of 21% compared to the cases with air coolant. Maintaining a constant mass flow rate, a further 20% average increase in cooling efficiency is observed when water coolant flow is used directly on the PV panel surface.

This improvement is attributed to the enhanced thermal dissipation capabilities of water. While efforts were made to ensure uniform water injection distribution for surface cooling, the potential for even more efficient cooling exists by increasing the number of jets and the water pump pressure. It is crucial to note that a comprehensive evaluation of the cooling procedure cannot be complete without considering the associated energy consumption, a topic that will be addressed in the subsequent figures.

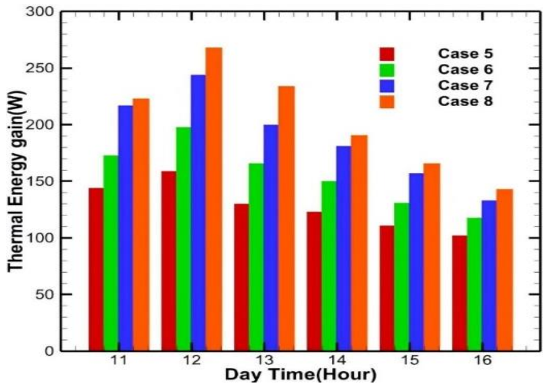


Fig. 5. The thermal energy gained for case 5, case 6, case 7, and case 8

The bifacial-hybrid cooling configuration for Cases 9 and 10, as depicted in Fig. 6, serves to highlight the optimal method for heat collection. In both cases, water cooling is applied directly on the PV surface, while air blows through the bottom channel in Case 9, and water flows in Case 10. Notably, Case 10 demonstrates a superior cooling performance, surpassing Case 9 by approximately 10%. This outcome underscores the enhanced effectiveness of using water for both sides of the PV panel compared to the combination of air and water cooling. Remarkably, Case 10 achieves over 100% and 90% higher heat transfer compared to the cases utilizing air and water coolant exclusively in the bottom channel. In contrast, Case 9 records correspondingly lower values of 88% and 81% compared to the air and water-cooled cases.

It is crucial to note that these findings align with the qualitative patterns observed in solar irradiance (Fig. 3a). The exceptional performance of Case 10 underscores the significance of employing a consistent cooling medium on both sides of the PV panel, providing valuable insights for the optimization of bifacial cooling strategies. These results signify a substantial advancement in our understanding of bifacial-hybrid cooling configurations and their implications for heat dissipation in arid weather conditions.

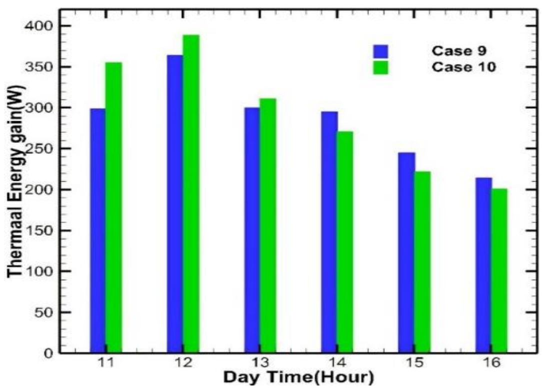


Fig. 6. The thermal energy gained for case 9, and case 10

Fig. 7 serves as a comprehensive visual representation of the thermal, electrical, and total efficiency in air-cooled PV panels for Cases 2 to 4. Initially, the graphical depiction reveals a consistent pattern where thermal efficiency is lower than electrical efficiency, a characteristic expectation in such systems, with the difference approximately at a factor of 1.5. This deepens as the impact of varying air mass flow rates unfolds. Increasing the air mass flow rate by a factor of 1.5 brings about a 20 percent increase in thermal efficiency and a 10 percent rise in electrical efficiency. On the other hand, decreasing the mass flow rate by about 60 percent makes a decrement of 17 and 8 percent, respectively in the thermal and electrical efficiency. The physical explanation of these trends can be attributed to improved heat dissipation from the PV panel surface and optimized semiconductor performance at higher air mass flow rates. Comparisons with the testimonial case (Case 1) show the tangible benefits of air cooling, with electrical efficiency surpassing the testimonial case by 1.5, 3, and 4 percent for mass flow rates of 0.024, 0.043, and 0.061 kg/s, respectively. Notably, the air cooling enables the PV panel to capture over 40 percent of the incident solar energy at its peak, highlighting the practical implications of these efficiency improvements.

The enhancement in cooling through water flow, as exemplified in Fig. 5, manifests in overall efficiency, as depicted in Fig. 8. Incrementing the water flow rate in the bottom channel introduces a substantial improvement, with thermal and electrical efficiencies experiencing an average increase of approximately 50 and 63 percent, respectively. The reverse trend is found by decreasing the water mass flow rate by decreasing the corresponding efficiency by about 40 and 51 percent. The notable enhancement is, however, subject to a higher pressure loss associated with water flow, presenting a trade-off between cooling efficiency and system considerations. Despite this, the electrical efficiency, in most cases, makes an uplift due to water coolant application, reaching up to a 50 percent increase compared to Case 1. Particularly, the water cooling in a channel heat exchanger demonstrates its ability by capturing about 50 percent of the incident solar energy at its maximum. Furthermore, optimizing the cooling system by utilizing injection nozzles on the PV surface allows for achieving higher heat transfer with a lower mass flow rate. It is such that the flow rate of about 1.5 L/min on the surface can act similarly to a flow rate of 2.5 L/min in the channel in terms of changing electrical and thermal efficiencies.

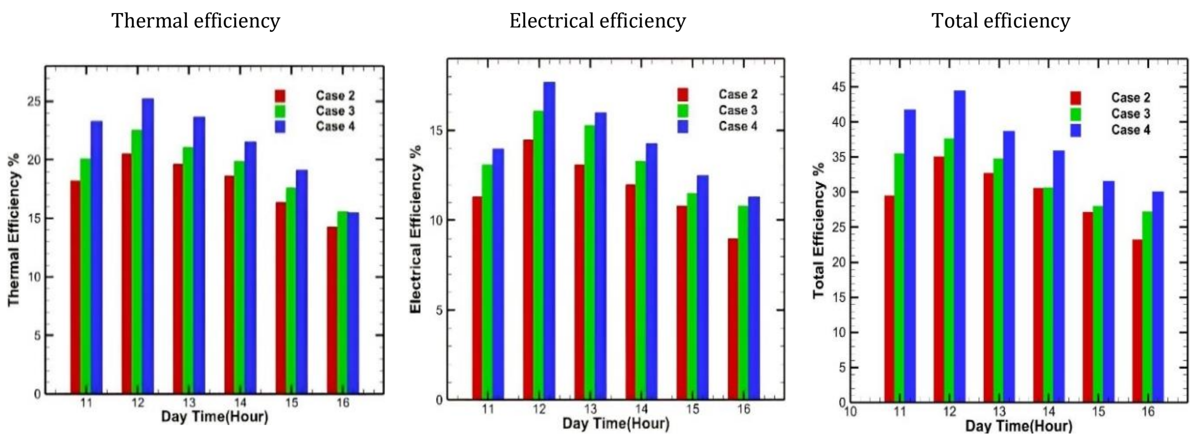


Fig. 7. Thermal, electrical, and total efficiency for case 2, case 3, and case 4

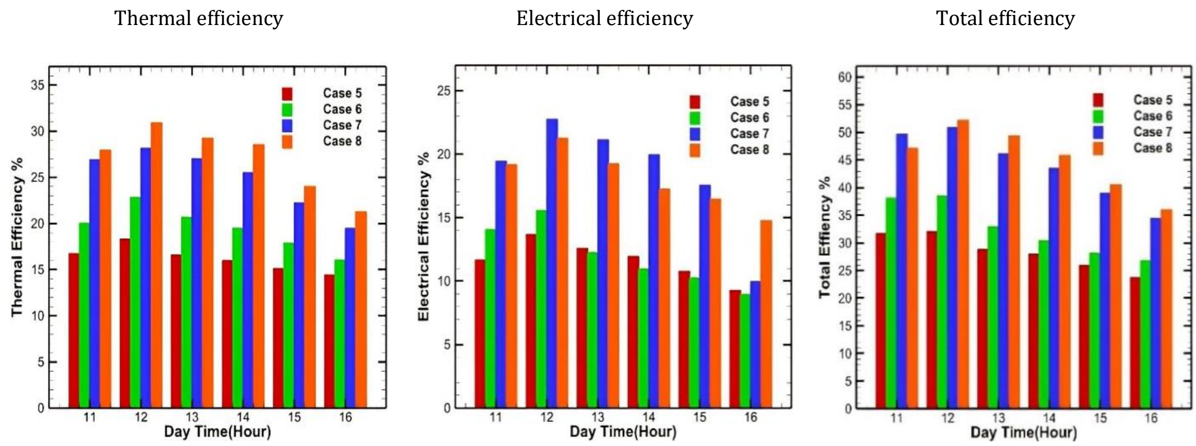


Fig. 8. Thermal, electrical, and total efficiency for case 5, case 6, case 7, and case 8

In Fig. 9, it is evident that hybrid cooling enhances efficiencies significantly. Among the tested cases, Case 9 exhibits the highest efficiencies, particularly in terms of thermal efficiency. This is attributed to the lower power demand for air-blowing. Comparing Case 9 to Case 10, the electrical efficiency is approximately 5 percent higher, while the thermal efficiency shows a substantial improvement of about 40 percent, on average. Specifically, Case 9 demonstrates a thermal efficiency that is, on average, 100 percent higher for air-cooled cases and 90 percent higher for water-cooled cases, respectively. In comparison, Case 10 shows an improvement of nearly 40 percent and 50 percent, respectively. When considering the electrical efficiency, both Case 9 and Case 10 elevate the values by a factor of about 2 and 1.8 for the air and water-cooled cases, respectively. At noon, the maximum achievable total efficiency for the current setup reaches approximately 68 percent, which is observed in Case 9.

Therefore, it is strongly recommended to implement hybrid cooling on both sides of the PV system using water and air in order to achieve the highest efficiency. The losses of the PV panel decreased considerably from more than 70 percent for the cases that use air coolant to lower than 50 percent for hybrid cases, on average, considering the balance energy in Eq. (4). The efficiency achieved in the current work is higher than that reported in previous studies. For example, Refs. [13], [17], and [21] mentioned efficiencies ranging from 10 to 16.3 percent. Additionally, Ref. [28] achieved an overall efficiency of approximately 40 percent. However, the total efficiency in the hybrid cases of the current work can surpass these values. Therefore, the current hybrid method has the potential to achieve even higher efficiency compared to similar studies. This is attributed to the fact that the current study exclusively utilizes a hybrid method that has not been previously applied in the literature.

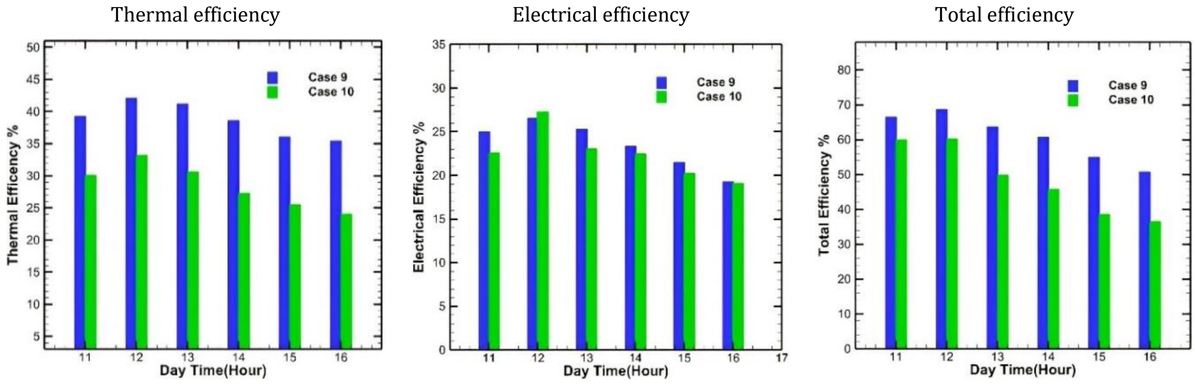


Fig. 9. Thermal, electrical, and total efficiency for case 9, and case 10

The COE is presented in Fig. 10 for cases 2 to 4. The values obtained are greater than unity, indicating higher net energy generation in the cooled PV system compared to the uncooled one. As time passes, the COE decreases by an increase in both the numerator and denominator of the COE equation. Additionally, the COE is observed to decrease with an increase in the coolant mass flow rate. By increasing the mass flow rate from the minimum to the maximum value, a decrement of approximately 3.5 percent in the COE can be achieved.

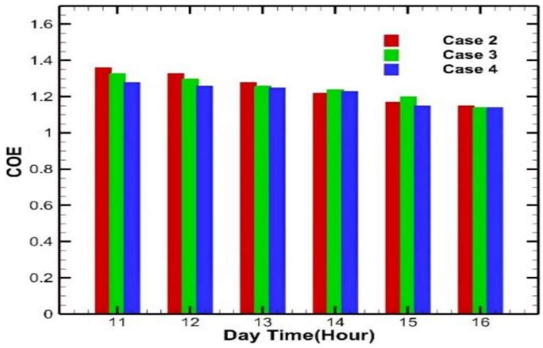


Fig. 10. The COE for case 2, case 3, and case 4

The implementation of water cooling in the channel results in a lower COE compared to the cases with air cooling, as shown in Fig. 11. This is primarily attributed to the higher energy loss associated with water pumping. By increasing the water coolant mass flow rate, the COE is decreased by an average of 20 percent. On the other hand, water cooling on the surface of the PV increases the COE due to increased power generation.

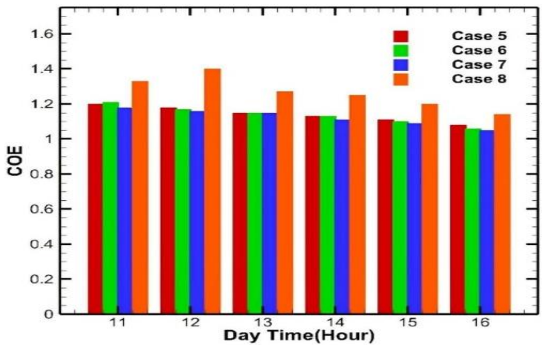


Fig. 11. The COE for case 5, case 6, case 7, and case 8

The increment in COE, compared to the cases with water channel cooling, is more than 60 percent, as depicted in Fig. 12. The results indicate that hybrid cooling, using air in the channel and water jets on the PV surface, provides a higher COE compared to the cases with water cooling in the channel, with an increase of approximately 10 percent. This is mainly attributed to the higher electricity generation achieved. Conversely, the COE is lower for cases with water cooling on both sides compared to the hybrid use of air and water, with a reduction of about 20 percent. These findings suggest that implementing water cooling in the channel, along with the use of hybrid cooling, can lead to improved COE and ultimately enhance the overall efficiency of the system.

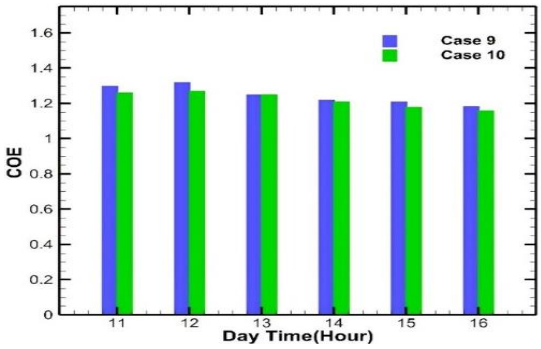


Fig. 12. The COE for case 9, and case 10

Before concluding the discussion, it is worthwhile to compare the efficiency achieved in the current study with those reported in similar earlier works. As presented in Table 4, in

Table 4. A comparison between the current results and those earlier published: electrical, thermal and overall efficiency

Ref.	Description of the study	Electrical Efficiency (%)	Thermal Efficiency (%)	Overall Efficiency (%)
Sweelem et al. [9]	Submerging PV panels in water	-	-	15.5
Krauter [10]	Water flow over the front of PV panels	-	-	30
Fang et al. [11]	PVT water cooling	-	-	10.9
Wu et al. [12]	PVT water cooling	8.45	63.65	-
Kumar et al. [13]	PVT air cooling with fins	10.5	15	-
Nizetic et al. [18]	PV water spray cooling applied on the surface	-	-	16.3
Nahar et al. [20]	PVT with parallel plate airflow cooling	-	-	20
Hassan et al. [22]	PV water cooling	-	-	16.2
Chin et al. [23]	PV with guided channels in cold plate	2	8	10
Khalaf et al. [25]	Solar photovoltaic collector by open water cycle jet-cooling	10.2	82.3	92.5
Rejeb et al. [26]	Solar PV/Thermal collector cooling water	13.7	58	-
Zhou et al. [41]	Water-cooled PVT collector with serpentine tube	14.5	52	-
Kazem et al. [42]	Water cooling PVT with spiral type flow channel tube	9.1	26	35
Jakhar and Sonu [43]	PVT collectors with earth-water heat exchanger	8.26	44.6	-
Boumaaraf et al. [44]	Water-glazed PVT collector	6.26	74. 2	-
Kazemian et al. [45]	Unglazed PVT/Water system	14.35	63.37	-
Omer et al. [46]	PVT water system	10.9	51.25	62.15
Menon et al. [47]	PVT system water cooling	14.58	58.77	80
Current Study	Air cooling (case 2, 3 and 4)*■	21.5	14.5	37.7
	Water cooling (5, 6 and 7) *■	24.4	18.91	45.16
	Hybrid (case 9)*	39.3	23.3	61.16

* average on time, ■ average on cases

comparison to the earlier related works, the electrical efficiency obtained in the current study is the highest, even when considering air cooling alone. This indicates that the cooling methods employed in the current study, particularly water cooling, and hybrid waterjets/air-cooling, have contributed significantly to improving the electrical energy production of the PV panels. Furthermore, the hybrid cooling method used in the current study has shown considerably higher efficiency compared to the values reported in other publications. However, it is important to note that the thermal efficiency of the current work does not reach the higher values achieved in similar studies. This may be attributed to the fact that not all of the water used for cooling is collected and stored, as some of it evaporates or is lost during the process.

Despite the limitations in thermal efficiency, the overall efficiency of the current study surpasses the majority of values presented in the literature. These findings underscore the significance of employing hybrid cooling techniques to improve the efficiency of PV panels. In summary, when comparing the current results to those reported in similar earlier studies, it is evident that the current study has made substantial advancements in terms of achieving higher electrical efficiency and overall efficiency.

4. Conclusions

The study provided the experimental investigation of bifacial cooling utilizing air and/or water in arid weather conditions. The implemented methodology involved the integration of a channel heat exchanger at the bottom of the PV panel and the application of water nozzles on the PV surface. Throughout the experimentation, rigorous analyses were conducted, encompassing the calculation of thermal energy captured, thermal and electrical efficiencies, and the coefficient of energy (COE). It is crucial to highlight that, despite the insightful findings presented, certain knowledge gaps persist in the current understanding of bifacial cooling technologies. The uncertainties inherent in such works underscore the need for further research and exploration in specific aspects of bifacial cooling, particularly in optimizing the interaction between cooling techniques and environmental conditions. By acknowledging and addressing these knowledge gaps, future investigations can contribute to refining the efficacy and applicability of bifacial cooling strategies for enhanced solar panel performance. The subsequent bullets summarize the key outcomes of this study and propose avenues for future research to bridge the identified gaps in knowledge.

- By increasing the mass flow rate, the cooling as well as thermal and electrical efficiency were raised. It was highlighted by using water coolant compared to air coolant.
- The heat captured by the hybrid-bifacial cooling improved by more than 90 percent compared to the cases with one type of coolant on one surface.
- By applying the water coolant, the thermal and electrical efficiency was raised respectively 50 and 63 percent compared to the air coolant case. Water cooling could enhance the electrical efficiency by 50 percent compared to the testimonial case.
- The highest total efficiency, equal to 68 percent, was achieved by bifacial cooling using air in the bottom channel and water jet nozzles on the panel surface. The thermal efficiency of the bifacial cases was respectively about 95 and 85 percent higher than the cases with respectively air and water cooling.
- The COE was also decreased by increasing the coolant mass flow rate, with a maximum of 3.5 percent. COE grew using water jets on the PV panel compared to the cases with the water in the bottom channel. The COE took lower values for cases with water cooling on both sides compared to the hybrid use of air and water by about 20 percent.
- Increasing the number of thermal sensors on the PV panel or in the heat exchanger channel will result in more detailed results and provide a temperature distribution for identifying the most thermally affected points. However, it was expensively hindered for this research.

Nomenclature

A	Surface area (m^2)
C_p	Specific thermal capacity (W/kgK)
$\dot{E}$	Power of Energy (W)
G_t	Global solar irradiance (W/m^2)
I	Electrical current (A)
$\dot{m}$	Mass flow rate (kg/s)
P	Power
$\dot{Q}$	Thermal energy gained (W)
$\dot{V}$	Volume flow rate (m^3/s)
T	Temperature (K)
V	Voltage (V)
Cooled/uncooled	Cooled/uncooled PV panel
elec	Electrical
in	Inlet
out	Outlet
Pumping	Owing to pump flow
PV	Photovoltaic
PVT	Photovoltaic thermal
OC	Open circuit
SC	Short circuit
th	Thermal

Acknowledgments

The authors wish to thank the Energy Research Institute and the Research & Technology Administration of the University of Kashan for their support regarding this research (Grant No. 1223100).

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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