An Experimental Investigation of Optimizing a Water-Based Photovoltaic Thermal (PVT) System through Reduced Tube Spacing

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ABSTRACT

Elevated temperatures in Photovoltaic (PV) cells significantly reduce their electrical efficiency, posing a major challenge to the advancement of the PV technology. While several cooling strategies have been proposed to address this issue, many remain inefficient due to the inadequate heat transfer between the cooling medium and the PV surface. In this study, a rear-side cooling system comprising 16 closely spaced parallel pipes was developed to enhance the heat dissipation from the PV module to the cooling water, improving the performance of Photovoltaic-Thermal (PVT) systems. Experimental evaluations were conducted to assess the effectiveness of the proposed system in comparison with a conventional PV module. The findings demonstrate that the highest cell temperature of the PV module is 62 °C at noon, corresponding with the greatest irradiation value of 1020 W/m². At the same time, the PVT system's highest cell temperature is 43.7 °C. This 29.25% decrease in the cell temperature increased the maximum power, improving the electrical efficiency by 11.75% during water cooling.

Keywords-Photovoltaic Thermal System (PVT); electrical performance; sustainable energy; distance between tubes

I. INTRODUCTION

The utilization of solar energy sources significantly contributes to mitigating the environmental challenges and meeting the growing global energy demand [1]. In developing countries, the advancement of solar energy technologies is particularly important, as it offers a sustainable and effective solution to reduce the energy poverty and promote the economic development [2]. PV panels are extensively employed to harness solar energy; however, a substantial portion of the incident sunlight is reflected from the panel surface. As a result, most of the absorbed energy is converted into excess heat within the PV module, while only a small fraction is transformed into electricity [3]. To recover this otherwise wasted thermal energy, PVT systems have been developed to enable the simultaneous generation of electricity and useful heat for various applications [4, 5]. In PVT systems, a working fluid circulates through a conduit to absorb the excess heat, thereby lowering the temperature of the PV cells and improving the system's overall efficiency. Considerable research has focused on enhancing the PVT system performance. Various aspects of the PVT design have been extensively examined, including the collector configurations [6], the concentrated PVT systems [7], the use of different working fluids [8], and the integration of Phase Change Materials (PCMs) [9]. Among these factors, the choice of cooling fluid plays a particularly critical role, with air and water being the most commonly employed. However, air-based PVT systems typically exhibit limited heat removal capabilities due to the inherently poor thermophysical properties of the air, such as low density, specific heat capacity, and thermal conductivity [10, 11]. In contrast, water-based PVT systems have gained increasing attention due to the superior thermophysical properties of water, which overcome the limitations of air-based systems and significantly enhance the thermal and electrical performance [11].

Researchers have explored various PVT collector configurations, including serpentine [12], spiral [13], channel [14], web flow [15], and split flow [16] designs. These configurations have been evaluated through both experimental investigations and numerical simulations using computational tools, such as COMSOL Multiphysics and ANSYS Fluent.

A computational study [17] on a box-channel PVT collector showed that increasing the mass flow rate, especially under high irradiance, significantly enhanced the energy performance. A numerical study examined a parallel-plate PVT configuration, showing that increasing the inlet water velocity from 0.0009 to 0.05 m/s led to a reduction in the average cell temperature to around 42 °C and an efficiency improvement of nearly 2% [18]. A coiled heat exchanger integrated into a PVT collector achieved 79.43% of the thermal efficiency through combined thermal and electrical energy collection [19]. Various cooling techniques for polycrystalline PV modules, air, water, nanofluid, and water spray were evaluated in [20]. The best performance came from front-side water cooling, which reduced the cell temperature by 29.37% and improved the efficiency by 6.84%. Simulations of a serpentine-flow PVT design demonstrated that increasing the flow rate and number of loops effectively reduced the cell temperature, though a greater number of loops also increased the pressure drop [21].

Most previous studies have investigated single-loop cooling collectors attached to the rear side of PV modules, utilizing designs, such as serpentine, spiral, and split configurations [22]. Although these systems provide some thermal enhancement, they often suffer from uneven heat removal across the panel surface due to the progressive rise in the coolant temperature along the flow path [22]. As a result, the inlet side of the panel is effectively cooled, while the outlet side experiences reduced cooling efficiency, which leads to elevated PV cell temperatures and diminished electrical performance [23].

To address this limitation, the present study introduces a novel rear-side cooling design consisting of 16 parallel cooling tubes with minimal spacing, uniformly distributed across the back surface of the PV module. This configuration is intended to promote a more consistent distribution of the coolant and improve the heat extraction efficiency over the entire panel area.

The primary objective of this study is to design and empirically assess this multi-tube cooling system to improve the electrical performance of PVT modules.

II. RESEARCH METHODOLOGY

A. Experimental Setup

The experimental test was performed in the city of Derna (32.75°N, 22.63°E), located on Libya's eastern coastline. The solar modules were installed at a tilt angle corresponding to the site's latitude, facing south with a fixed inclination of 32.7°. The experimental configuration comprised two monocrystalline solar modules, each with a maximum power output of 75 W. One module was left unmodified as a reference, while the second module was integrated into a PVT system that included an absorber sheet and water-based cooling tubes, as illustrated in Figure 1.

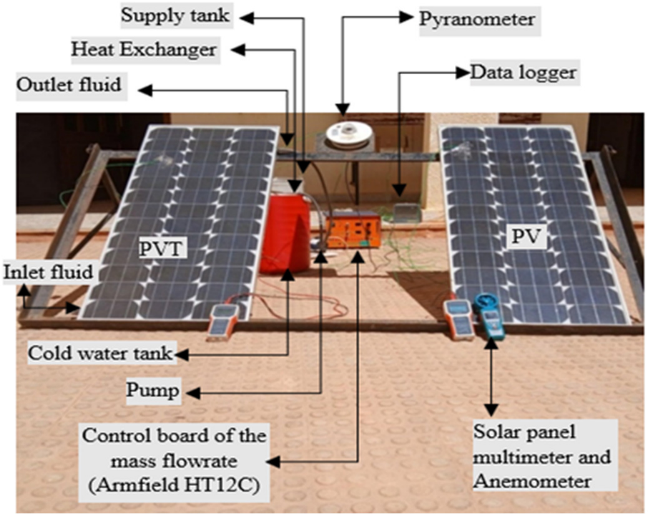


Fig. 1. Experimental setup.

The PVT system included a heat exchanger fabricated from parallel copper tubes placed at a minimal distance apart. These tubes were configured and welded to a copper absorber plate, which was affixed directly to the rear surface of the PV module using DTH thermal grease, known for its high thermal conductivity. The absorber plate was in full contact with the back of the solar panel, with no air gap. To minimize the heat losses, the tubes and rear surface were fully insulated, followed by the installation of a wooden backing plate. Figure 2 displays the actual view of the proposed cooling PVT system. The cooling system's hydraulic design received special attention, particularly the inlet and outlet headers, which were engineered for hydraulic symmetry. Identical tube lengths and diameters were used to ensure a uniform flow resistance, and the header connections were symmetrically arranged to minimize the pressure variations. This configuration guaranteed a consistent distribution of coolant across the 16 parallel tubes, reducing the pressure drop discrepancies and enhancing the overall thermal uniformity. The PVT system's detailed specifications are listed in Table I. Both the PVT and reference PV modules were tested under identical environmental conditions on a clear day in August 2024, with data recorded every 15 min. The measurements included the slope irradiance, ambient temperature, PV surface temperature, outlet water temperature, and maximum power output. The working fluid was kept in a 15-L tank and moved by a pump at a steady rate of 48 L/h controlled by an electronic valve (Armfield HT12C) between the inlet and the pump. A spiral heat exchanger inside the storage tank cooled the heated fluid after it passed through the PVT panel. Temperature measurements were acquired using five K-type thermocouples with a resolution of ±0.75%. Two thermocouples were attached to the front surfaces of the PV and PVT modules to monitor the surface temperatures, two were positioned at the inlet and outlet of the PVT system to evaluate the temperature rise of the working fluid, and one was used to record the ambient air temperature. The thermocouples used have a typical response time of less than 1 s, which is sufficient for the steady-state measurements conducted in this study. All thermocouples were affixed using thermally conductive adhesive to ensure proper thermal contact and minimize the contact resistance. A multi-channel data logger (MPR5000ST) recorded both the temperature and solar irradiance, while wind speed was measured using a digital anemometer (TETAND1) with a resolution of ±2%. The maximum power output of both systems was measured using two solar panel multimeters (Model: EL400B) with an accuracy of ±0.01% every 15 min. Figure 3 depicts the entire test setup, including various devices.

Fig. 2. The actual view of the proposed cooling PVT system.

B. Uncertainty Analysis of Measured Data

Performing uncertainty analysis is essential when undertaking experimental investigations. Thus, a comprehensive assessment of uncertainty was conducted to verify the reliability of the measurement outcomes. The procedure for analyzing uncertainty includes the utilization of (1-5), as specified in [24]:

$$X_m = \frac{1}{N}\sum X_i \tag{1}$$

where X_m represents the mathematical average of the measured data, X_i signifies the ith measure of the given variable, and V_r denotes the variation.

To evaluate the standard deviation, measurements were repeated over two consecutive days, with durations ranging between 4 and 5 h, resulting in a total of N=35 measurements for each calibrated variable. The standard deviation (S) and measurement uncertainty (U) of the instruments were calculated using [24]:

$$V_r = \frac{1}{N-1}\sum({X_i}^2 - {X_m}^2) \tag{2}$$

$$S = \sqrt{V_r} \tag{3}$$

$$a = \frac{1}{\sqrt{N}} \tag{4}$$

$$U = \sqrt{\sum_{i=1}^{R} a_i^2 \; S_i^2} \tag{5}$$

For the computed quantities, the uncertainty of the power output and electrical efficiency of the PV module is estimated by [25]:

$$\frac{\delta P_{mp}}{P_{mp}} = \left(\left(\frac{\delta I}{I}\right)^2 + \left(\frac{\delta V}{V}\right)^2\right)^{1/2} \tag{6}$$

For instance, according to the relative uncertainty values for voltage ($\frac{\delta V}{V}$=1.2) and current ($\frac{\delta I}{I}$=0.85) listed in Table II, by applying these values to (7), the total relative uncertainty in the power output is calculated as:

$$\frac{\delta P_{mp}}{P_{mp}} = ((0.85)^2 + (1.2)^2)^{1/2} = 1.47\% \tag{7}$$

The uncertainty of the electrical efficiency is calculated as:

$$\frac{\delta \eta_{el}}{\eta_{el}} = \left(\left(\frac{\delta I}{I}\right)^2 + \left(\frac{\delta V}{V}\right)^2 + \left(\frac{\delta G}{G}\right)\right)^{1/2} \tag{8}$$

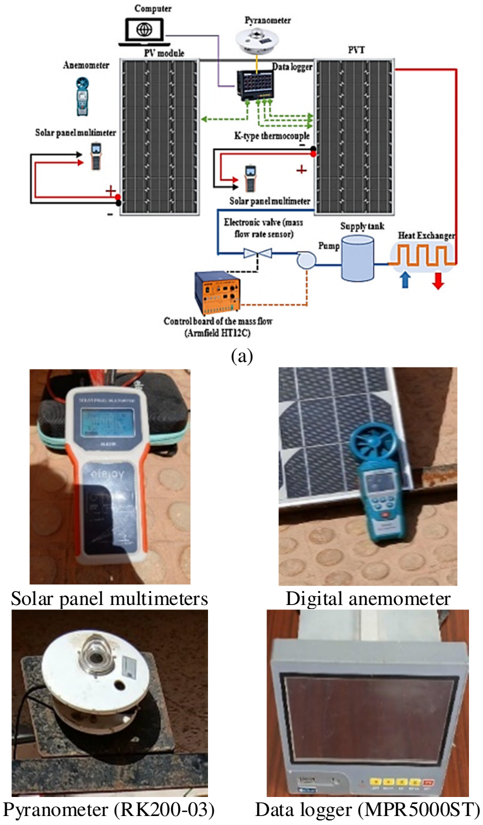
Throughout the assessment period, the experimentally measured percentage uncertainty of the PV system's power production and electrical efficiency is determined to be 1.47% and 2.2%, respectively. Table II presents the experimental evaluation equipment and output uncertainties.

TABLE I. DETAILED SPECIFICATIONS OF THE PVT SYSTEM

Layer	Parameter	Value
PV module	Max power (P_{mp})	75 W
	Current, short circuit (I_{sc})	4.78 A
	Voltage, open circuit (V_{oc})	21.6 V
	Current max (I_{mp})	4.33A
	Voltage max (V_{mp})	17.3 V
	Cell efficiency	15%
	Module area (A_s)	0.592 m^2
Absorber plate (copper)	Thickness (δ)	0.002 m
	Length (L)	1.03 m
	Width (W)	0.51m
Tube (copper)	Inner diameter (D_i)	0.009 m
	Outer diameter (D)	0.01 m
	Number	16
	Space between tubes	0.03 m
Insulation	Thickness	0.03 m
	Length (L)	1.1 m
	Width (W)	0.51 m
Wooden cover	Thickness (δ)	0.005 m
	Length (L)	1.13 m
	Width (W)	0.52 m

TABLE II. THE EQUIPMENT AND OUTPUT UNCERTAINTIES OF THE PV SYSTEM

	Devices	Unit	Total uncertainty (%)
Solar irradiation	Pyranometer	W/m^2	±2.8
Temperature	Thermocouples	^{o}C	±0.48
Mass	Flow sensor	L/min	±0.01
Wind speed	Anemometer	m/s	±0.28
PV voltage	Multimeter	V	1.2
PV current	Multimeter	A	0.85
Electrical power		W	1.47
Electrical efficiency		%	2.2



(a)

Solar panel multimeters
Digital anemometer
Pyranometer (RK200-03)
Data logger (MPR5000ST)

(b)

Fig. 3. Experimental setup: (a) complete test configuration and (b) measurement instruments.

C. Performance Assessment

To assess the electrical efficiency of the PV panels, the electrical power output (P_{mp}) from every module may be determined by calculating the product of the observed current (I_{mp}) and the voltage (V_{mp}) that follows:

$$P_{mp} = I_{mp} \times V_{mp} \tag{9}$$

The solar energy (P_{in}) captured by the PV modules may be derived from the observed solar radiation (G) by:

$$P_{in} = G \times A_s \tag{10}$$

The parameter A_s represents the surface area of the PV panels that receive solar radiation. The PV model's electrical efficiency is expressed as:

$$\eta_{el} = \frac{P_{mp}}{P_{in}} \tag{11}$$

To better understand this performance behavior, the relative improvement (ξ_{el}) in PV electrical efficiency is defined and computed by:

$$\xi_{el} = \frac{\eta_{el,PVT} - \eta_{el,PV}}{\eta_{el,PV}} \times 100 \tag{12}$$

III. RESULTS AND DISCUSSION

The main aim of this study is to investigate the impact of the proposed cooling configuration on lowering the PV cell temperature, and hence improving the module's electrical performance. Experimental assessments were conducted to evaluate the efficacy of the proposed PVT system and to compare its performance with that of a standard PV module. The reference PV module and the PVT module were evaluated under the same outside environmental conditions on a clear day in August 2024. Data were collected at 15-min intervals over a continuous testing duration from 08:00 to 16:00. Throughout the testing phase, the environmental conditions displayed regulated variations. Solar irradiance fluctuated from 348.8 W/m² at 08:00 to a peak of 1020.12 W/m² at solar noon, while the ambient temperature ranged from 26.3°C at 08:00 to 35.3°C at 12:15, as seen in Figure 4. Temperatures and sun irradiance were quantified utilizing K-type thermocouples and a solar pyranometer, respectively. The wind speed was measured continuously throughout the day using a digital anemometer. The coolant flow rate in the PVT system was consistently regulated at 48 L/h by a controlled pumping mechanism. The peak electrical power output of both systems was assessed using calibrated solar panel multimeters. Furthermore, the comprehensive uncertainty analysis previously given was largely undertaken to validate the reliability and calibration precision of the measurement devices employed in the experimental setup. The subsequent sections delineate the experimental data acquired from both the PV and PVT units, accompanied by a comprehensive comparison and analysis illustrated graphically.

Figure 5 illustrates the temporal evolution of PV cell temperatures for both the proposed PVT system and the standalone PV unit throughout the experimental duration. During the experimental period, the PV cell temperature in the conventional system consistently remained higher than that of the water-cooled PVT system. The PV reference unit reached a peak cell temperature of 62.0 °C at peak solar irradiation (12:00), whereas the PVT system maintained significantly cooler cell temperatures at 43.7 °C under the same circumstances. This is a significant 29.5% decrease in the maximum cell temperature. This was achieved by employing back-surface cooling for PV panels, which involves the circulation of water through copper circular tubes.

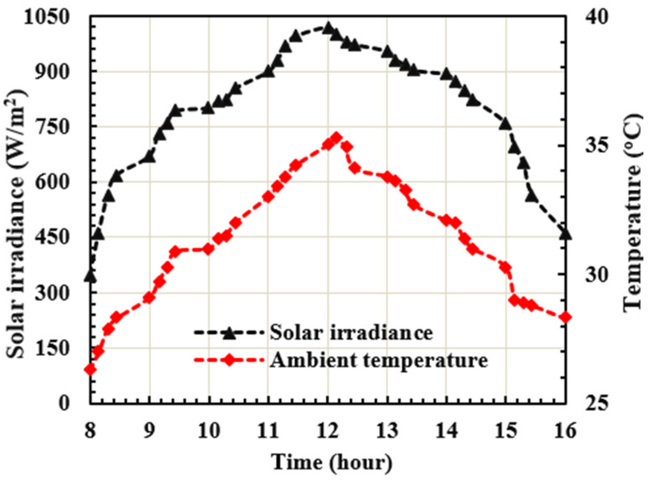


Fig. 4. Solar irradiation and ambient temperature during the test day.

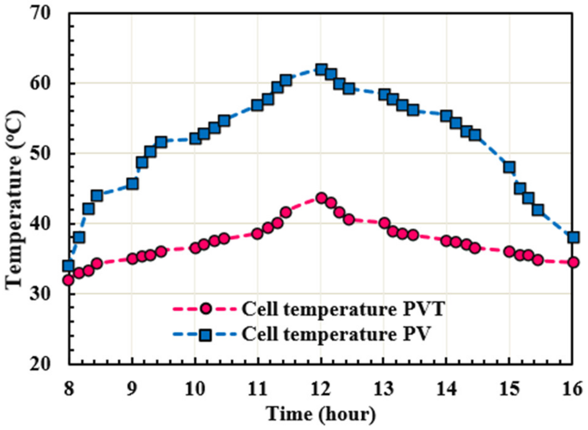


Fig. 5. The temporal evolution of the PV cell temperature for both the PVT system and the PV module during the test day.

Table III displays the correlation between an average rise in the cell temperature and each 100 W/m² increment in solar irradiation. Studies show that the temperature of the cells rose by an average of 2.52 °C [13], 1.85 °C [14], and 2 °C [20] for every 100 W/m² of more solar irradiation. This study indicated that the proposed PVT system attained a mean cell temperature elevation of 1.64°C for each 100 W/m² rise in solar irradiance, which is inferior to the PVT systems examined in prior research. The temperature rises indicate the ability of PV modules employing various cooling techniques to withstand temperature elevations for each 100 W/m² increment in solar irradiation. The cooling system demonstrated efficacy in reducing further temperature rises, as decreased cell temperatures sustained elevated electrical efficiency. This study involved the design of a PVT system featuring minimal spacing between parallel pipes to optimize the distribution of the cooling fluid on the solar panel's rear side. This configuration improved the convective heat exchange characteristics, facilitating a better heat transfer from the PV panels into the cooling water.

TABLE III. COMPARISON WITH PREVIOUS WORKS

Reference	**Cooling duct configuration**	**Solar irradiance (W/m^2)**		**Cell temperature rise per 100 W/m² of solar irradiance (°C)**
		At the start of the period	At the peak of the period	
[17]	Spiral heat exchanger	200	1000	2.52
[14]	Copper serpentine heat exchanger	1000	3000	1.85
[20]	Rectangular channel	650	1068	2
Present work	Parallel tubes with little separation	348	1020	1.64

Figure 6 presents a comparison of the maximum power output and electrical efficiency of a PV module, with and without a water-cooling system, derived from experimental testing. The PV system integrated with a water-based cooling mechanism demonstrates significantly superior performance, attaining a higher power output and an improved electrical efficiency. This is due to the water-back surface cooling mechanism incorporated in the PVT system, leading to a considerable decrease in the solar cell temperature. Without cooling, the PV module exhibits an efficiency of 10.21% and an output power of 60.81 W at a cell temperature of 62 °C. When the water-back surface cooling system is utilized, the cell temperature decreases to 43.7°C, leading to a notable enhancement in the electrical efficiency to 11.41% and a power output of 68.16 W. This signifies an increase of around 11.75% in the electrical efficiency relative to the standard PV panel lacking cooling.

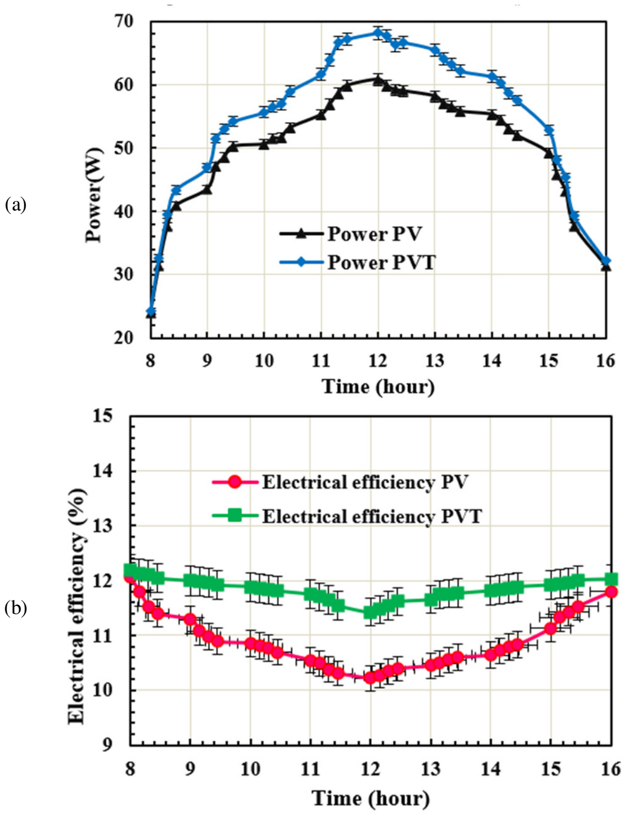


Fig. 6. The temporal evolution of: (a) maximum power and (b) electrical efficiency for both the PVT system and the PV module during the test day.

Figure 7 exhibits the temporal variation of relative improvement (ξ_{el}) in electrical efficiency for the water-cooled PVT system compared to the uncooled reference PV system. Despite the comparable testing circumstances, including direction, incoming solar irradiance, and ambient air temperature, a clear variation was observed due to the incorporation of cooling pipes on the back surface of the PVT system. These pipes contributed to enhanced thermal management are not present in the conventional PV system. In the initial part of the experiment, diminished solar irradiation levels led to a drop in the heat transfer to the cooling water, resulting in comparable performance between both systems and an associated fall in the relative enhancement of the cooled system. The second period (08:45-14:45) exhibited the most significant performance enhancement, with the water-cooled system demonstrating average improvements of around 10.63% in the electrical efficiency relative to the reference system. This significant enhancement is directly associated with the increased thermal energy transfer to the coolant medium. Finally, in the period (15:00–16:00), a significant decrease in the performance increase was observed, with efficiency improvements declining to 1.95%. This drop correlates with the declining solar irradiation levels at which the PV modules cease to get significant benefits from further cooling. The data show that the effectiveness of the cooling system is dependent on the amount of the solar radiation incident and the consequent thermal stress on the PV modules.

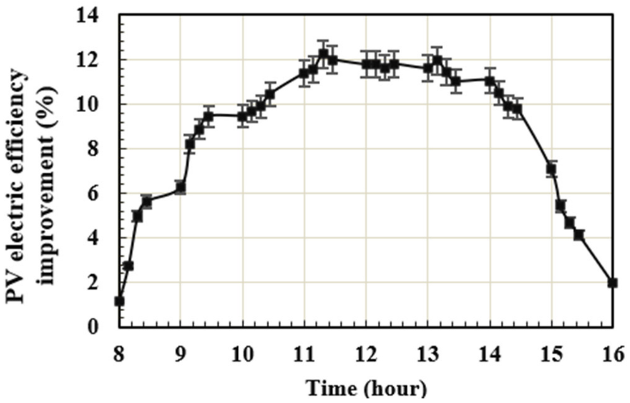


Fig. 7. Relative improvement in electrical efficiency over time for the water-cooled PVT system.

IV. CONCUSION

This study involved a detailed experimental evaluation of a water-based Photovoltaic-Thermal (PVT) system, developed with the aim of mitigating the thermal non-uniformity on the rear side of Photovoltaic (PV) modules. To achieve this, the system design focused on minimizing the spacing between the cooling tubes to promote a more uniform heat removal. The proposed configuration incorporated 16 parallel copper tubes, evenly distributed across the back surface of the PV panel. This arrangement was intended to enhance the coolant flow uniformity, resulting in improved convective heat transfer and more efficient thermal regulation of the PV cells.

The experimental results confirmed that reducing the distance between the tubes led to a more consistent temperature profile across the entire module. Compared to the conventional, uncooled PV system, which exhibited a peak cell temperature of 62 °C during maximum irradiance, the cooled PVT system reached a significantly lower temperature of 43.7 °C. This notable reduction in operating temperature directly contributed to an improved electrical performance. The electrical efficiency of the cooled module was measured at approximately 11.41%, compared to 10.21% in the reference PV module, reflecting the beneficial impact of the enhanced heat dissipation.

The findings underscore the importance of tube spacing in the thermal management of PVT systems. The closer spacing not only improved the cooling effectiveness, but also ensured a more homogeneous thermal behaviour across the panel surface, which is essential for maintaining long-term efficiency and performance stability. Furthermore, the results indicated that the effectiveness of the cooling configuration was strongly influenced by the solar irradiance levels. The greatest performance improvements were recorded during periods of high solar intensity, suggesting that such systems are particularly advantageous in sunny climates or regions with high average insolation.

REFERENCES

[1] A. A. Melaibari, N. H. Abu-Hamdeh, A. S. Alorfi, H. A. Al-Bonsrulah, and A. M. Elsiddieg, "New design for PVT system with elliptic cooling duct involving nanofluid in existence of MHD and utilizing TEG," *Case Studies in Thermal Engineering*, vol. 53, Jan. 2024, Art. no. 103815, https://doi.org/10.1016/j.csite.2023.103815.

[2] M. Sheikholeslami and Z. Khalili, "Investigation of nanofluid cooling influence on energy performance of photovoltaic-thermoelectric module," *Journal of Thermal Analysis and Calorimetry*, vol. 149, no. 1, pp. 495-503, Nov. 2024, https://doi.org/10.1007/s10973-023-12710-3.

[3] A. K. Azad and S. Parvin, "Photovoltaic thermal (PV/T) performance analysis for different flow regimes: A comparative numerical study," *International Journal of Thermofluids*, vol. 18, May 2023, Art. no. 100319, https://doi.org/10.1016/j.ijft.2023.100319.

[4] M. N. Hanani, J. Sampe, J. Jaffar, and N. H. M. Yunus, "Development of a Hybrid Solar and Waste Heat Thermal Energy Harvesting System," *Engineering, Technology & Applied Science Research*, vol. 13, no. 3, pp. 10680-10684, Jun. 2023, https://doi.org/10.48084/etasr.5561.

[5] S. Almoatham, A. Chiasson, R. Mulford, and M. Moreno-Pena, "Development of experimentally validated models for nocturnal cooling of thermal systems with photovoltaic thermal (PVT) modules," *Solar Energy*, vol. 268, Jan. 2024. , Art. no. 112279, https://doi.org/10.1016/j.solener.2023.112279.

[6] Y. Jia, G. Alva, and G. Fang, "Development and applications of photovoltaic‑thermal systems: A review," *Renewable and Sustainable Energy Reviews*, vol. 102, pp. 249-265, Mar. 2019, https://doi.org/10.1016/j.rser.2018.12.030.

[7] M. M. A. El-Samie, X. Ju, Z. Zhang, S. A. Adam, X. Pan, and C. Xu, "Three-dimensional numerical investigation of a hybrid low concentrated photovoltaic/thermal system," *Energy*, vol. 190, Jan. 2020, Art. no. 116436, https://doi.org/10.1016/j.energy.2019.116436.

[8] M. Hissouf, M. B. Feddaoui, M. Najim, and A. Charef, "Performance of a photovoltaic-thermal solar collector using two types of working fluids at different fluid channels geometry," *Renewable Energy*, vol. 162, pp. 1723-1734, Dec. 2020, https://doi.org/10.1016/j.renene.2020.09.097.

[9] M. G. Kibria, M. S. Mohtasim, U. K. Paul, B. K. Das, and R. Saidur, "Impact of hybrid nano PCM (paraffin wax with Al2O3 and ZnO nanoparticles) on photovoltaic thermal system: energy, exergy, exergoeconomic and enviroeconomic analysis," *Journal of Cleaner Production*, vol. 436, Jan. 2024, Art. no. 140577, https://doi.org/10.1016/j.jclepro.2024.140577.

[10] A. S. E. Souissi, M. Masmali, M. Fterich, E. Touti, and H. Chouikhi, "3D Numerical Study and Parametric Analysis of PV/T Design Effect on Thermal and Electrical Performance," *Engineering, Technology & Applied Science Research,* vol. 14, no. 3, pp. 14175-14182, Jun. 2024, https://doi.org/10.48084/etasr.7227.

[11] S. Abdul-Ganiyu, D. A. Quansah, E. W. Ramde, R. Seidu, and M. S. Adaramola, "Study effect of flow rate on flat-plate water-based photovoltaic-thermal (PVT) system performance by analytical technique," *Journal of Cleaner Production*, vol. 321, Oct. 2021, Art. no. 128985, https://doi.org/10.1016/j.jclepro.2021.128985.

[12] S. S. Park, Y.-J. Kim, E.-C. Kang, E.-J. Lee, and E. Entchev, "Numerical investigations of a solar energy heat transfer performances with experimental validations in a water-based serpentine photovoltaic-thermal (PVT) collector," *Journal of Thermal Analysis and Calorimetry*, vol. 148, no. 5, pp. 2149-2169, Dec. 2022, https://doi.org/10.1007/s10973-022-11861-z.

[13] M.-W. Tian *et al.*, "Energy, exergy and economics study of a solar/thermal panel cooled by nanofluid," *Case Studies in Thermal Engineering*, vol. 28, Dec. 2021, Art. no. 101481, https://doi.org/10.1016/j.csite.2021.101481.

[14] R. Nasrin, M. Hasanuzzaman, and N. Rahim, "Effect of high irradiation on photovoltaic power and energy," *International Journal of Energy Research*, vol. 42, no. 3, pp. 1115-1131, Oct. 2017, https://doi.org/10.1002/er.3907.

[15] H. A. Kazem, A. H. Al-Waeli, M. T. Chaichan, K. H. Al-Waeli, A. B. Al-Aasam, and K. Sopian, "Evaluation and comparison of different flow configurations PVT systems in Oman: A numerical and experimental investigation," *Solar Energy*, vol. 208, pp. 58-88, Sep. 2020, https://doi.org/10.1016/j.solener.2020.07.078.

[16] A. Kazemian, T. Ma, and Y. Hongxing, "Evaluation of various collector configurations for a photovoltaic thermal system to achieve high performance, low cost, and lightweight," *Applied Energy*, vol. 357, Mar. 2024, Art. no. 122422, https://doi.org/10.1016/j.apenergy.2023.122422.

[17] R. Nasrin, M. Hasanuzzaman, and N. Rahim, "Effect of high irradiation and cooling on power, energy and performance of a PVT system," *Renewable Energy*, vol. 116, pp. 552-569, Feb. 2018, https://doi.org/10.1016/j.renene.2017.10.004.

[18] A. Nahar, M. Hasanuzzaman, N. Rahim, and S. Parvin, "Numerical investigation on the effect of different parameters in enhancing heat transfer performance of photovoltaic thermal systems,"*Renewable Energy*, vol. 132, pp. 284-295, Mar. 2019, https://doi.org/10.1016/j.renene.2018.08.008.

[19] B. Boumaaraf, H. Boumaaraf, M. E.-A. Slimani, S. Tchoketch-Kebir, M. S. Ait-Cheikh, and K. Touafek, "Performance evaluation of a locally modified PV module to a PV/T solar collector under climatic conditions of semi-arid region," *Mathematics and Computers in Simulation*, vol. 167, pp. 135-154, Jan. 2020, https://doi.org/10.1016/j.matcom.2019.09.013.

[20] T. Nabil and T. M. Mansour, "Augmenting the performance of photovoltaic panel by decreasing its temperature using various cooling techniques," *Results in Engineering*, vol. 15, Art. no. 100564, Sep. 2022, https://doi.org/10.1016/j.rineng.2022.100564.

[21] S. Aghakhani, M. Afrand, A. Karimipour, R. Kalbasi, and M. M. Razzaghi, "Numerical study of the cooling effect of a PVT on its thermal and electrical efficiency using a Cu tube of different diameters and lengths," *Sustainable Energy Technologies and Assessments*, vol. 52, Aug. 2022, Art. no. 102044, https://doi.org/10.1016/j.seta.2022.102044.

[22] L. T. Kostić and J. S. Aleksić, "Review of research, development and application of photovoltaic/thermal water systems," *Open Physics*, vol. 18, no. 1, pp. 1025-1047, Dec. 2020, https://doi.org/10.1515/phys-2020-0213.

[23] M. E. H. Attia, M. E. Zayed, A. Kabeel, A. Khelifa, M. Arıcı, and M. Abdelgaied, "Design and performance optimization of a novel zigzag channeled solar photovoltaic thermal system: Numerical investigation and parametric analysis," *Journal of Cleaner Production*, vol. 434, Jan. 2024, Art. no.140220, https://doi.org/10.1016/j.jclepro.2023.140220.

[24] G. Yıldız, A. E. Gürel, F. Katırcıoğlu, and Ü. Ağbulut, "Energy, exergy, environment and economic (4E) analysis of PV/T module assisted vapor compression refrigeration system: An experimental study," *Heliyon*, vol. 10, no. 19, Oct. 2024, Art. no. e37690, https://doi.org/10.1016/j.heliyon.2024.e37690.

[25] A. Hassan *et al.*, "An experimental and numerical study on the impact of various parameters in improving the heat transfer performance characteristics of a water based photovoltaic thermal system," *Renewable Energy*, vol. 202, pp. 499-512, Jan. 2023, https://doi.org/10.1016/j.renene.2022.11.087.