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Impact of Different Parameters on Power Generation from Photovoltaic Module Cooled by Three-Sided Water Spray

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ABSTRACT

The conversion efficiency of photovoltaic solar panels is significantly impacted by accumulated heat in the module materials, and significant reduction is experienced with the high temperature of the PV upper surface. Cooling, such as water spray cooling, is essential to maintain proper PV performance. The objective of this research is to investigate the spray water temperature and flow rate to cool down the panel and to determine the effect on the energy efficiency of the PV panels. The design of a front surface cooling system by water spray in a three-sided water inlet pattern was experimentally and computationally developed and investigated. ANSYS Fluent was utilized to predict the effects of the proposed system on PV power production. The results indicated that the proposed system, with a water flow rate of 5 L/min, has increased the power production of PV by 20.3%. The simulation finds novelty in the impact of ambient temperature and solar irradiation on cooled PV power produced. When the ambient temperature increased from 35 to 50℃, the reduction in power is 3.2 W, which is very small compared to the non-cooling system. The power production was boosted by 16.6% when the solar radiation increased by 100 W/m² and the PV surface temperature raised by 0.5℃ based on the water flow rate of 5 L/min.

1. INTRODUCTION

Maximizing universal population and economy are leading to an increase in Annual Primary Energy usage by 1.6% (British Petroleum Company [1]). Authenticity increasing the indigence of energy is preferable to be offered by cheaper, reliable and no contamination sources. According to the British Petroleum Company, 2018, 85% of the energy that the universe consumes is from non-renewable energy roots. This rate should be decreased briskly by replacing it with renewable energy sources due to its effect on global warming and environmental alter. Therefore, researchers focused on utilizing renewable energy instead of conventional once. Solar energy is the most widespread renewable energy nowadays.

Typically, photovoltaic (PV) efficiency ranges from 10% to 20% [2]. Bazilian et al. [3] documented that 80-90% of PV panels' low power production is related to converting solar radiation to heat energy. An essential point for PV to produce higher power is to have a low operation temperature. Cooling the front surface of a PV panel will result in increasing the performance of the panel, therefore producing higher power. Lately, researchers and scientists have been working on developing different PV cooling designs. Some researchers were the first to start to cool the panel by utilizing air and water. Wolf [4] used a combined solar panel system with a heating system, while Florschuetz [5] was the first scientist who implement air to cool down the panel. Another study used water to cool down PV panels in conjunction with flat plate solar collectors [6], while Hendrie [7] studied the effect of utilizing air and water to improve panel efficiency. Research in the field of submerging the front face of the panel has been experimentally studied by Safitra et al. [8]. The influence of submerging the front face of the panel in water at varying levels and velocities of flow. The findings suggested that the lowest level of water immersion generated the highest efficiency. Another study conducted an optimization of panel cooling using spray water, which was addressed as an effective method for the hot region. The result showed that the solar array efficiency was increased by 16.65%. Also, they conclude that this design needs less space and also it is less expensive compared with other cooling systems [9].

The PV performance was investigated by decreasing the space between the nozzles and the PV panel to the smallest distance, which was 10 cm the power output was increased to 25.86% [10]. The authors progressed a cooling system that consisted of three nozzles with a 90° spraying angle, and an on/off controller was managed as 30 on 180 seconds off was capable of maximizing the efficiency by 2.09℃ and the panel temperature was minimized up to 24℃ [11]. Jailany et al. [12] demonstrated that by applying forced water spraying over the surface of the panel by using a water distribution hose, it was possible to reduce the temperature of the panel by up to 9.07℃ over 10 hours. In a separate study by Govardhanan et al. [13], the PV panel was cooled by having three distinct flows of uniform water go over the top surface of the panel. It was concluded that cooling the PV module reduced the panel temperature by 30%, resulting in increased power production from 19 to 23 W. Additionally, it was concluded that the front surface water cooling system was advantageous for clearing the panel surface of dust, resulting in enhanced visual appearance. Due to a study made in 2019 by Zhe et al. [14] using ANSYS CFX to determine the distribution of temperature of PV modules by using front surface cooling at different water inlet temperatures, the findings showed that the panel mean temperature for not cooled one was about 50.68℃, while it was 45.34℃ and 29.71℃ for water inlet temperature 45℃ and 20℃ respectively. Another research by Syafiqah et al. [15] utilized ANSYS Fluent to study the impact of five distinct water flow rates ranging from 0.01 to 0.05 kg/s on panel cooling and their effect on convection heat transfer rate. The results indicated that the convection heat transfer rate will be considerably reduced by increasing the flow rate, which will be 235 W at 0.05 kg/s.

Khalil et al. [16] studied the front surface cooling by applying six nozzles, two from the top and two at each left and right side of the panel, exactly facing each other. Their outcome indicates that the maximum power output improvement rate using the proposed method was 15.5%. Other researchers used PV back cooling to enhance the efficiency. El-Seesy et al. [17] studied the panel performance by using four mirrors to concentrate the radiation on the panel, and they used 8 rectangular aluminum tubes under the panel to cool down the panel. They found out that the output of a bifacial concentrated panel with cooling is about three times the power produced by the normal panel. Bevilacqua et al. [18] used different ways to cool down the panels on the back surface by using water spraying and forced convection to overcome the high temperature. The results showed maximization in the efficiency by 1.6%. Hossain et al. [19] developed a novel type of heat exchanger positioned at the back of the panel to cool down the cells using air. The maximum improvements they came within the voltage and output power were 1.3 V and 7.4 W, respectively. In another study by Muslim et al. [20], a cooling chamber attached with three different pane orientations with 60°, 30° and 0° angles to the back side of the PV panel with two different flow directions, up flow and down flow, the result showed that module 1 has maximum efficiency about 80% with flowrate 4 L/min and electrical efficiency 17% with 60° pane orientation. Rosli et al. [21] used ANSYS software to validate an experimental result of back cooling by using a spiral absorber to study the effect of water inlet temperature and solar radiation intensity over the temperature stability. They conclude that a flow rate of 40 kg/h and solar irradiance range of 800 to 1000 W/m^2 is the most suitable operating condition to maintain temperature stability and high performance. Rasool and Abdullah [22] developed an experimental PV panel with a rear-side water-cooling chamber, testing flow rates of 1.5 to 3.5 L/min. The results showed that electrical efficiency increased by up to 19.72% and thermal efficiency by up to 79.2%. This highlights the effectiveness of water cooling in enhancing PV panel performance. Another study by Al-Ghezi et al. [23] reviewed various cooling methods for PV panels, focusing on environmental and economic impacts. Thermoelectric and evaporative cooling emerged as the most promising, improving energy efficiency and being economically viable.

The concept of PV cooling has been extended to cooling in the day and warming in the night. A novel approach has been introduced by Al-Kayiem and Reda [24] and Reda et al. [25] to cool the PV panel during the day when the surface temperature goes above 40℃ and warming the panel during the night to eliminate the confidence film created by the humidity condensation on the panel surface. They achieved this colling/warming method by circulating water between the backside tank of the PV panel and the underground buried coil. They reported that the temperature reduced lower than the dew point, and water droplets started to accumulate and enlarge to create a water layer film over the surface. This phenomenon is very unfavorable as it encourages the sand particles to collate with the water film and produce a mud layer on the PV surface.

In this study, a new proposed PV cooling by water spray pattern has been demonstrated. The three-side water spray pattern has not been studied yet based on the literature, and the impact of various parameters on the efficiency and power production of cooled PV panels is to be determined. This research aims to conduct a rigorous investigation into the performance of cooled PV panels under varying conditions, combining experimental and theoretical approaches. Specifically, the study seeks to elucidate the key factors impacting PV power output, such as ambient temperature, solar irradiance, and water inlet temperature during summer conditions prevalent in the northern region of Iraq. Additionally, the research endeavors to develop and validate a novel cooling pattern through advanced theoretical modeling utilizing ANSYS Fluent software.

This research compares the theoretical and experimental results by applying a three-side-water spray pattern to a PV panel front surface and examines which factors will most affect its power production. The novelty of this study lies in identifying the operating conditions that will mostly affect cooled PV panel power production. Furthermore, it provides valuable insights for the installation of PV panels in appropriate areas, which will result in maximum power production.

This investigation examines the efficacy of a three-side water spray pattern on a PV panel and endeavors to identify which factors have the greatest influence on its power output. A unique feature of this study is the use of a modified three side spray pattern to enhance the performance of the PV panel, as well as to recognize the key factors influencing its power production. It is anticipated that the findings of this research will be beneficial to PV module manufacturers and researchers, allowing them to optimize the performance and output of their products.

2. METHODOLOGY

The monocrystalline PV panel was experimentally tested with and without surface cooling by spraying water with a new design to maintain the thickness of water across the panel surface so that most of the panels would have the same temperature distribution. Four different volume flow rates were examined: 2, 3, 4, and 5 L/min and simulated by ANSYS Fluent with the same flow rates. Also, by using ANSYS Fluent, it was tested which factor mostly affects the PV power production ambient temperature, solar radiation, or water inlet temperature at all flow rates of water.

2.1 Experimental investigation

An experimental system is formulated to enhance the performance of a monocrystalline photovoltaic panel by front surface cooling by spraying water at four different flow rates as compared to a reference one without cooling. The prototype is developed, fabricated and installed at Erbil Polytechnical University- Research Center. Figure 1 presents a schematic diagram of the two monocrystalline photovoltaic modules, which are facing south with an inclination angle of 36° corresponding to the latitude of Erbil. Technical features of PV panels at nominal operating conditions of 25°C temperature and solar irradiance 1000 W/m^2 and 1.5 m/s are presented in Table 1.

Table 1. Technical features of PV at standard operating conditions (25°C, 1000 W/m^2, 1.5 m/s)

Parameters	Value
Module dimension (mm)	1330×670×30
Module weight	9 kg
Nominal power	206 W
Cell efficiency	23.04%
Maximum power current (Imp.p)	7.68 A
Maximum power voltage (Vmp.p)	27.31 V
Open circuit voltage (Voc)	31.41 V
Short circuit current (Isc)	8.2 A
Nominal operating cell temperature	25°C
Working temperature	-40°C - +80°C

The test apparatus employed in the experimental PV module is depicted in Figure 2. It consists of a steel support structure, PV panels, water pumps, primary and secondary storage tank of 250 liters, motorized valve, water filter, datalogger, batteries 25 V, 5 Amp DC connected in series, MPPT solar charger controller, and DC load.

The cooling system consists of 6 nozzles placed over the panel in a three-sided pattern so that the thickness of water over the panel will be uniform and all the panels will be at the same temperature at all times. Figure 3 presents the schematic and experimental rig location of nozzles over the panel.

The data logger was designed to record data every one-minute interval system; it measured temperature, voltage, current, solar intensity, and water volume flow rate. The Temperature sensors (K-type thermocouple) are connected to six analog channels measuring inlet and outlet water temperature for the water-cooling panel with three points on the panel surface and one sensor on the reference panel (without cooling). At the same time, the DHT11 temperature sensor measured the ambient temperature.

The two SEN32 REV1 volt sensors and two current sensors are utilized to gauge the panels' current and voltage. The YF-S401 sensor measures the water flow rate. Moreover, the solar irradiance was measured through a Digital Solar Power Meter (DBTU1300). The experimental study was run during the summer months. The longitude and latitude of Erbil city are 44.009° and 36.191°, respectively. The tilt angle of both panels is 36°, facing the south direction. The daily test runs from 8 AM - 3 PM. Eq. (1) was employed to calculate the panel power, while Eq. (2) was used to determine the electrical efficiency of the panels [26].

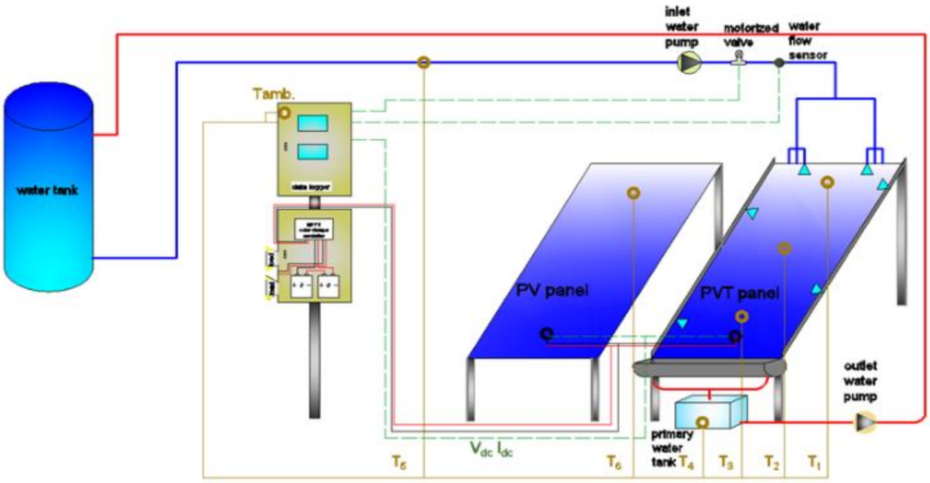

Figure 1. Schematic diagram of the experimental system

Figure 2. Photovoltaic panels experimental rig

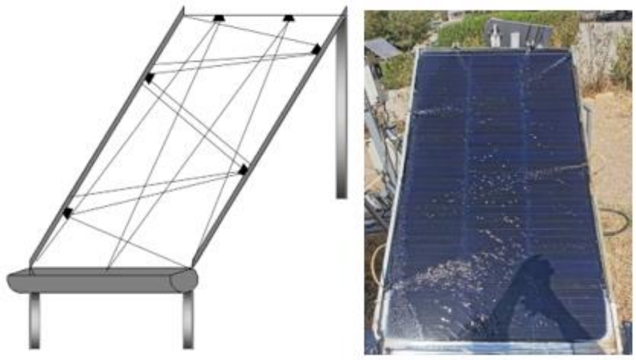

Figure 3. Schematic diagram and experimental rig of nozzles location over the panel

$$P = I \times V \tag{1}$$

$$\eta_{electrical} = \frac{I \times V}{I_s \times A_{panel}} \tag{2}$$

where, P is the power output from the module, and $\eta_{electrical}$ is the electrical efficiency, I_s is the solar irradiation (W/m^2), A_{panel} is the panel area (m^2), and I and V are the current (Amp) and voltage (Volt) of the panel, respectively.

2.2 Uncertainty

Calculating the uncertainty of the measurements is important, as it allows the researcher to assess the accuracy of the results during the experiment. It provides a measure of how close the obtained values are likely to be to the true values. Without considering uncertainty, the measured values may be misleading or misinterpreted. Uncertainty can minimize random errors, whereas effective calibration procedures can eliminate systematic errors [27]. An equation has been used to calculate the uncertainty of the measurement [28, 29].

$$uncertainity\ (u) = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{N * (N-1)}}$$

where, N is the sample number, $\bar{x}$ is the average value of considered data for the variable x, the results of ith data is represented by x_i.

The results of the uncertainty of the measurements in this study are presented in Table 2.

Table 2. Uncertainty of the measurements

Instrument	Uncertainty
Flow meter	± 0.013
K-type thermocouple	± 0.08
Voltage sensor	± 0.05
Power sensor	± 0.09
DHT11 ambient sensor	± 0.08

2.3 Computational investigation

In a recent study, the three-dimensional geometry of a photovoltaic (PV) module with front surface water cooling was modeled using ANSYS R19.2. The model, depicted in Figure 4, illustrates the PV panel layers: glass, EVA1, silicon, EVA2, and Tedlar, with dimensions matching the experimental study. A thin film of water covers the panel's surface, serving as a cooling mechanism.

Unlike previous studies, which introduced water only from the top, this model incorporates water entry from the top, left, and right sides, with the outlet at the lower part, potentially enhancing cooling efficiency.

This simulation was conducted using ANSYS Fluent, a computational fluid dynamics (CFD) software. An automatic mesh has been applied to photovoltaic geometry, while for water layer inflation, the mesh was used to give precise temperature distribution, as shown in Figure 5. The generated mesh has zero skewness.

The grid independence test was also conducted to test the accuracy of the simulated result, as shown in Figure 6, where there was an average variation of 0.08% from the achieved result.

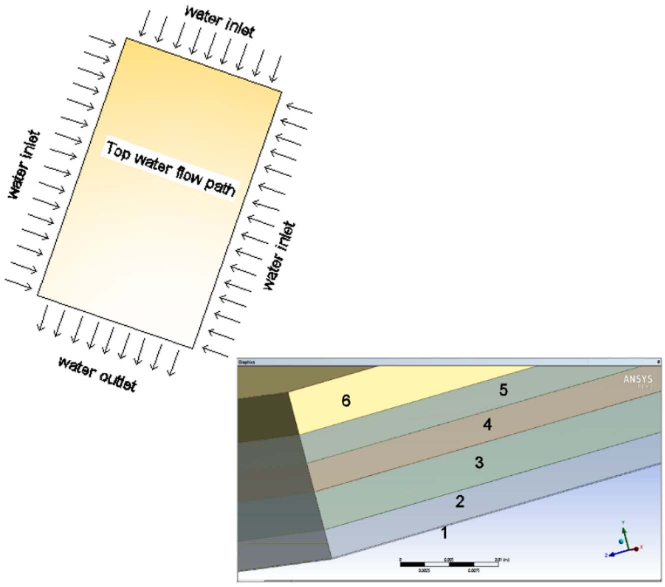

Figure 4. The geometry of the panel's layers with the water cooling system

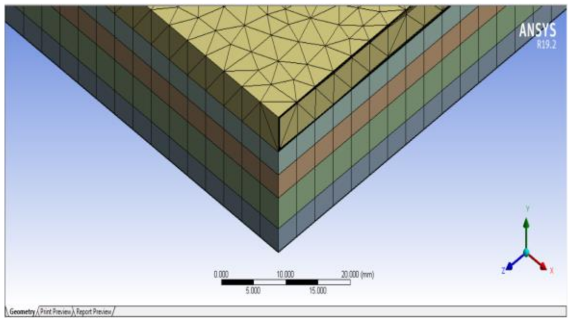

Figure 5. Photovoltaic water-cooling diagram of mesh in ANSYS

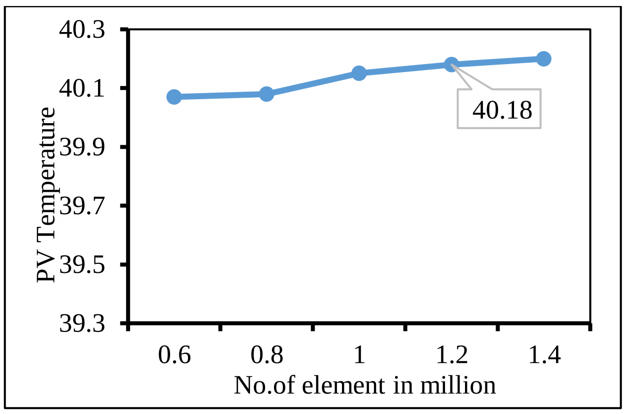

Figure 6. Grid independence test

Usually, the photovoltaic panel consists of five different solid layers: A glass covering on the outward-facing surface, Ethylene Vinyl Acetate (EVA1) serving as an encapsulation for the silicon, the silicon layer itself, which converts radiation into electricity, EVA2, and Tedlar on the rear surface. Each layer has its own specific thickness, heat capacity, density, and thermal conductivity, as presented in Table 3. The PV panel is topped by a layer of water that encompasses the entirety of the panel, with inlets located on the left, right, and upper sides and an outlet on the lower side. Then, the solid and fluid domains in the current computational fluid analysis were connected in such a manner that the transfer thermal features at the interfaces would be on target.

Table 3. Data for the layers of the panel used in ANSYS

Materials	Thickness (m)	Specific Heat Capacity (J/kg·°C)	Density (kg/m^3)	Thermal Conductivity (W/m·K)
Water	0.0045	4180	997	0.59
Glass	0.003	500	3000	0.98
EVA 1	0.003	2090	960	0.23
Silicon	0.004	712	2.329	148
EVA 2	0.003	2090	960	0.23
Tedlar	0.0001	1250	1200	0.36

CFD is a branch of fluid mechanics that is employed for the purpose of assessing the equations that govern the heat transfer in the photovoltaic (PV) water cooling system, which is comprised of both fluid and solid domains. The fluid domain is attributed to the water employed for cooling the PV, while the solid domain is attributed to the five distinct layers of the PV. Eqs. (3) and (4) present the heat transfer equation for solid and fluid domains, respectively [30]:

$$\rho_i C_{p,i} \frac{\partial T_i(x,y,z)}{\partial_t} = \nabla.(q_i) + Q_i \quad i = 1,2, \dots \dots n \tag{3}$$

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u.\nabla T(x,yxz) = \nabla.(q) + Q_{vh} \nabla.u = 0 \tag{4}$$

The equations of momentum and continuity equations are:

$$\rho \frac{\delta u}{\delta t} + \rho(u.\nabla)u = \nabla.\left[-pI + (\mu + \mu_T)(\nabla u + \nabla u^T) - \frac{2}{3}\rho k I\right] \tag{5}$$

$$\rho \nabla.u = 0 \tag{6}$$

The radiation model used is discrete ordinary (DO), which was used to apply solar radiation to the domains. Eqs. (7) and (8) are (DO) radiative transfer equations:

$$\nabla.(I(\vec{r}.\vec{s})\vec{s}) + (a + \sigma_s)I(\vec{r}.\vec{s}) = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I(\vec{r}.\vec{s}')\,\phi(\vec{s}.\vec{s}')d\Omega' \tag{7}$$

$$\nabla.(I_\lambda(\vec{r}.\vec{s})\vec{s}) + (a_\lambda + \sigma_s)I_\lambda(\vec{r}.\vec{s}) = a_\lambda n^2 I_{b\lambda} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I_\lambda(\vec{r}.\vec{s}')\,\phi(\vec{s}.\vec{s}')d\Omega' \tag{8}$$

where, λ is the wavelength, a_λ is the co-efficient of spectral absorption and $I_{b\lambda}$ is the intensity of the black body given by the Planck function. The other parameters, such as scattering phase function, scattering coefficient, and the refractive index, are assumed to be invariable despite variations in wavelength.

A steady state condition was applied for the simulation. Different water inlet temperatures, different ambient temperatures, and different radiation intensities at different water flow rates were tested. To examine the effect of these factors on panel power production, in contrast to the reference PV. The water volume flow rates used in this simulation are 2, 3, 4, and 5 L/min, while inlet water temperature ranges from 25 to 40°C, the examined ambient temperatures were 35, 40, 45, and 50°C, and the solar intensity examined were 600, 800 and 1000 W/m^2.

Different correlations were developed to calculate the power production for the simulation data of the PV module, and in the present research, the correlation used to calculate the power produced from the panel is [31]:

$$P = G_t \tau_{pv} \eta_{T_{ref}} A[1 - 0.0045(T_c - 25)] \tag{9}$$

where, τ_{pv} is the transmittance of the photovoltaic panel outer layers [32].

3. RESULT AND DISCUSSION

3.1 Experimental result

The experiments were conducted in Erbil-Iraq throughout August, from 8:00 AM to 3:00 PM. The purpose of the experiments was to analyze the efficacy of a photovoltaic system under varying water flow rates of 2, 3, 4, and 5 L/min in three side patterns and compare it to a reference panel without cooling. Table 4 illustrates the ambient temperature (Tamb.) and solar irradiance (I) during test days at each 15-minute interval from 8:00 AM to 3:00 PM.

Figure 7 presents the temperature of the PV panel at various flow rates. The data demonstrate that as the rate of flow increases from 0 to 5 L/min, the temperature of the PV panel decreases from 71.5 to 39.25°C. Increasing the flow rate of the cooling system can significantly lower the temperature of the photovoltaic module since the heat transfer rate is increased based on the increase in the water flow rate. Therefore, increasing the rate of water utilized to cool down the PV is an effective measure for maintaining the ideal temperature of the photovoltaic panel.

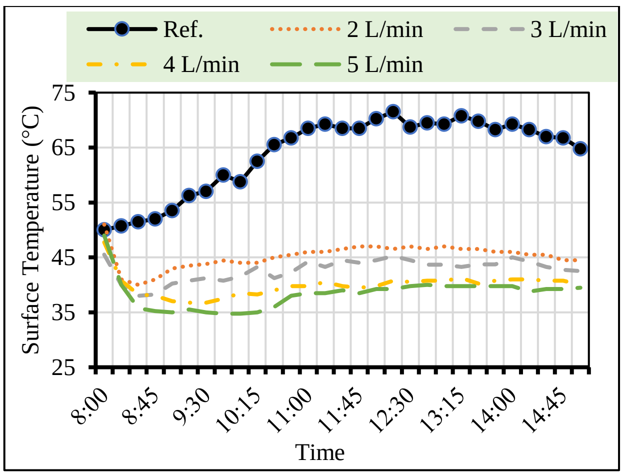

Figure 7. Transient PV surface temperature at different volume flow rates of spray water

Table 4. Ambient temperature and solar irradiance during test days

Time	7/8/2022		9/8/2022		10/8/2022		11/8/2022	
	Tamb. (℃)	I (W/m²)	Tamb. (℃)	I (W/m²)	Tamb. (℃)	I (W/m²)	Tamb. (℃)	I (W/m²)
8:00	39	435	36.9	410	36.8	470	36	465
8:15	39.7	465	37.1	463	37	504	36.2	497
8:30	40.2	530	37.2	531	37.2	536	36.7	537
8:45	41.9	605	37.8	620	38	606	37.6	595
9:00	43.3	660	40.7	655	38.6	670	38.4	660
9:15	43.6	730	41.5	739	39.7	738	39.5	720
9:30	44	770	40.7	786	39.2	780	39.5	764
9:45	43.7	820	40.9	823	40.5	825	39.6	812
10:00	43.6	865	42.7	879	39.8	858	39.5	840
10:15	43.7	895	43.4	898	41.6	888	40.5	880
10:30	44.6	914	42.4	912	43.4	918	41.8	900
10:45	43.9	950	45.3	940	44.1	940	42.2	933
11:00	44.6	976	43.4	973	45.4	971	42.7	976
11:15	43.6	983	43.8	998	45.2	988	43.5	990
11:30	45.3	995	44.4	1007	45.4	996	42.5	997
11:45	47.3	1012	44.7	1015	44.9	1008	43.9	1005
12:00	47.5	1036	43.4	1027	45.5	1017	44.5	1012
12:15	46.2	1030	46.7	1033	46.2	1017	44.8	1018
12:30	47.4	1039	45.5	1041	45.3	1022	44.9	1023
12:45	48.2	1037	46.2	1048	46.5	1019	45	1020
13:00	46	1022	46.8	1034	46.5	1008	43.5	1007
13:15	45.9	1010	46.3	1018	46.7	988	43.9	995
13:30	47	990	46.7	1009	46	971	44.7	978
13:45	46.3	985	45.7	994	46.8	950	44.5	942
14:00	46.7	966	47.8	960	46.8	920	44.3	920
14:15	46.7	922	45.7	934	46.8	890	44.4	899
14:30	47	898	46.3	915	47.3	876	44.7	879
14:45	46.9	863	45.2	875	47.4	854	44.7	844
15:00	45.8	830	46.9	834	46.2	818	44.7	822

Variation in power production during the daytime at different flow rates as compared to the reference panel without cooling is illustrated in Figure 8. It could be recognized that with increasing the flow rate, the power output from PV is increased as well.

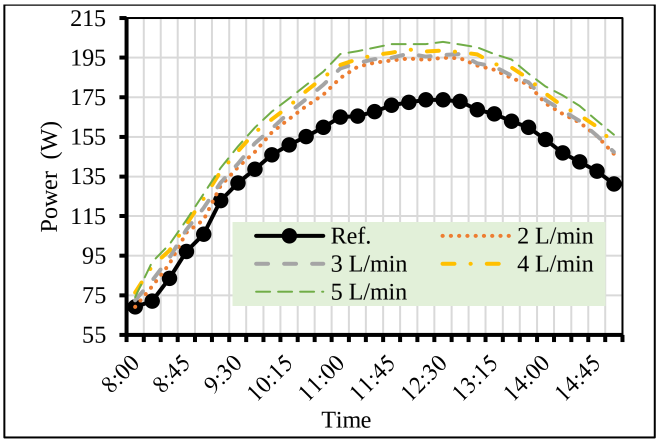

Figure 8. Variation of PV power production with time at different volume flow rates

The results indicate that cooling the panel with a flow rate of 5 L/min increases its power production more than all the other flow rates at all solar radiation values. This increase is much more significant during high solar radiation time as the power production is increased up to 20.5%, and this enhancement in power production is higher compared to the other literature, which is due to the new concept of the cooling pattern of the panel from three sides in a specific pattern which will cover all the cells of the panel and maximize the power production. At 12:30, the panel's output power was 173 W without cooling. When cooled with flow rates of 2 and 5 liters per minute, the power production increased to 194 and 203 W, respectively.

The results depicted in Figure 9 demonstrate that there is a significant improvement in electrical efficiency when the panel is cooled. This suggests that cooling the panel can significantly enhance its capability of producing power at various flow rates, with higher efficiencies being attained at higher flow rates. Thus, it can be inferred that the panel is able to generate power efficiently at any given flow rate and can be adjusted to suit the desired power output.

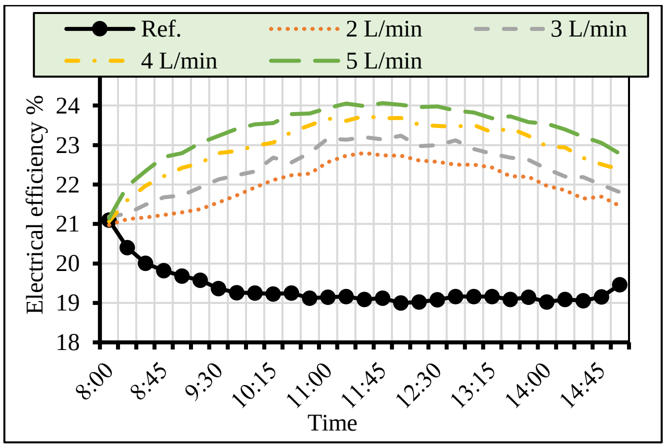

Figure 9. Variation of panel efficiency at different volume flow rates with time

The results of this experiment illustrate the importance of properly managing the cooling system of PV panels. As the rate of flow increases, the temperature of PV diminishes, making it more efficient and effective in its performance. The results indicate that the proper flow rate of the cooling system is crucial for the optimal performance of the PV panel. Cooling the panel with a flow rate of 5 L/min enhanced its power production by an average of 20.25%. In comparison, a flow rate of 2 L/min improves the PV production by only 10.38%.

Figure 10 presents the comparison of the spray water cooling technique applied on the PV panel performed by different researchers, on the other hand Risdiyanto et al. [33] used 8 nozzles on the back and front surface of the panel and results in an improvement of 9.03%. While, Sornek et al. [34] placed a header on the top of the panel to spray water over the panel, and the maximum enhancement rate in power production was only 10%. However, another study conducted in Egypt, Khalil et al. [16] studied the front surface cooling by applying six nozzles, two from the top, two at the left, and other two nozzles at the right side of the panel exactly facing the nozzles on the left side, and the maximum power output improvement rate was 15.5%. On the other hand, research where conducted in India by using 20 nozzles [35], 10 on the front side fixed at an angle of 40° with panel surface and 10 on the backside fixed perpendicular to that surface of the panel but the improvement was just 16.3%.

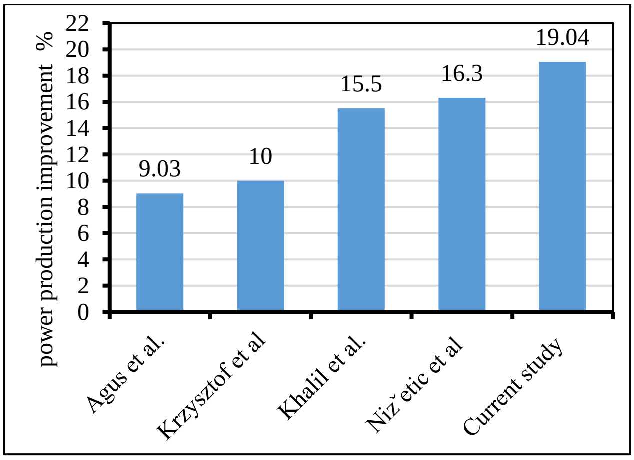

Figure 10. Comparison of panel power production improvement

The current study demonstrated that the use of spray water cooling from the front surface of a PV module at a volume flow rate of 5 L/min using 6 nozzles in a three-side pattern resulted in an improvement of 19.04% in power production. This improvement was attributed to the full coverage of the panel with water, which led to a decrease in the temperature of all the cells within the module and thus increased its performance in converting solar energy into electrical power. This study offers a noteworthy contribution and novelty to the field by demonstrating a high level of power production improvement percentage when compared to previously conducted studies.

3.2 Validation result

This section provides the validation results of experimental and ANSYS Fluent simulation outcomes concerning the performance of PV panels. A comparison of the two revealed that the simulation outcomes were in close accordance with the experimental one. The simulation results were within 1.08% of the experimental results, indicating that the model was valid and reliable for forecasting the performance of solar cells.

The comparison between PV temperature and water outlet temperature at different volume flow rates using ANSYS and the experimental result is illustrated in Figure 11. The temperature of the PV surface obtained from ANSYS and measured data are highly concordant, with the greatest disparity amounting to 0.6°C and the least to 0.3°C, which consider a variation of 1.39% and 0.3%, respectively.

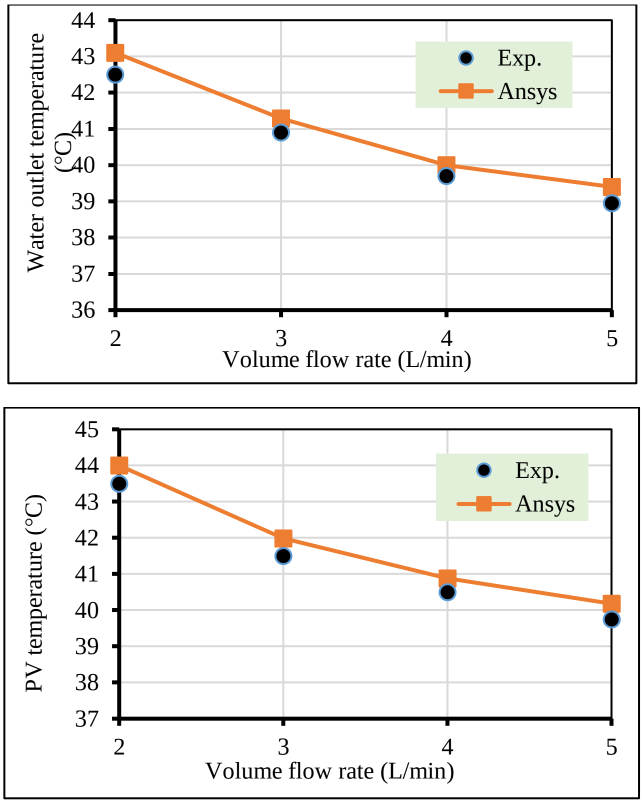

Figure 11. Comparison of numerical and experimental data at various volume flow rates

The results demonstrate that ANSYS can accurately predict the PV temperature at various rates of water. Furthermore, the outcome demonstrates that the cooling system can reduce the PV temperature, thus enhancing the dependability and steadiness of the photovoltaic system.

3.3 Computational results

This section presents the CFD results of the influence of various parameters (ambient temperature, water inlet temperature, and solar intensity) at various rates of water over the temperature and performance of panels. The investigation was conducted to evaluate the behavior of PV modules under diverse conditions.

Figure 12 illustrates the effect of different ambient temperatures over the panel power production and temperature at different water volume flow rates, at a constant water inlet temperature of 35°C and solar irradiance at 1000 W/m^2. As the ambient temperature rises from 35°C to 50°C, the PV panel temperature increases by 3.7°C and the power production is decreased by 3.2 W when the water flow rate was 2 L/min while at a maximum water-cooling flow rate of 5 L/min, the PV panel temperature raised by 2.6°C and the power production decreased by 2.3 W. This has happened because as ambient temperature increases, the temperature of the PV panel module rises due to increase in the thermal energy of the PV panel. The first law of thermodynamics governs this phenomenon. The increase in ambient temperature results in a reduction in the heat transfer rate between the PV panel and the surroundings.

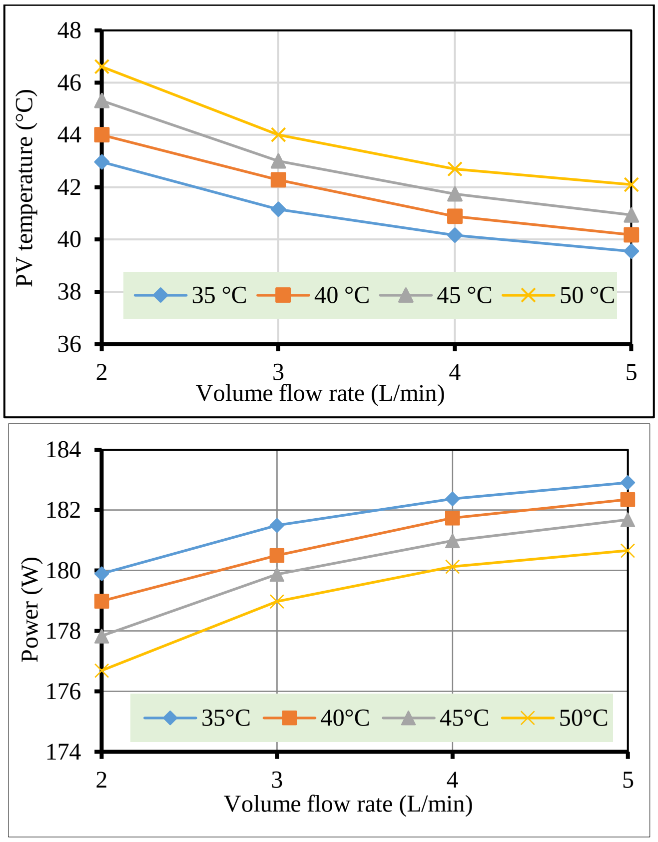

Figure 12. Variation of PV temperature and power production with flow rate at various ambient temperatures

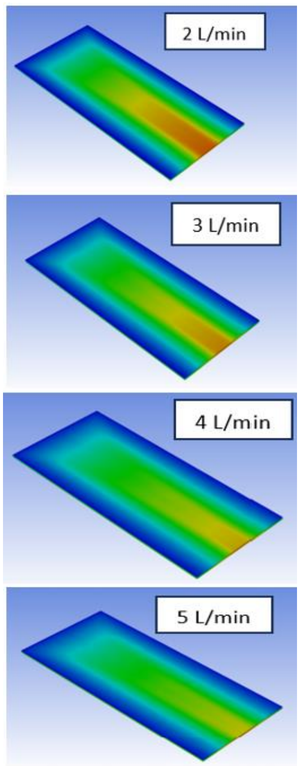

Figure 13. Variation in water temperature distribution at 35°C ambient temperature

The contour of temperature distribution of water over the panel surface at 35°C ambient temperature, 1000 W/m^2 solar irradiance, and 35°C water inlet temperature at volume flow rates of 2, 3, 4, and 5 L/min are shown in Figure 13.

Figure 14 illustrates the impact of varying irradiation intensity and water flow rate on PV temperature and power production, with a constant water inlet temperature of 35°C and an ambient temperature of 40°C. It can be observed from the results that increasing solar irradiation intensity from 600 to 1000 W/m^2 at a water flow rate of 5 L/min leads to a significant increase in the PV power production from 110.47 W to 182.35 W, while the panel surface temperature increased only 2°C. Conversely, a higher rate of water was seen to reduce the PV temperature substantially. So that the efficient cooling provided by higher water flow rates enables the PV system to handle increased irradiation intensity, resulting in enhanced power production with minimal temperature elevation.

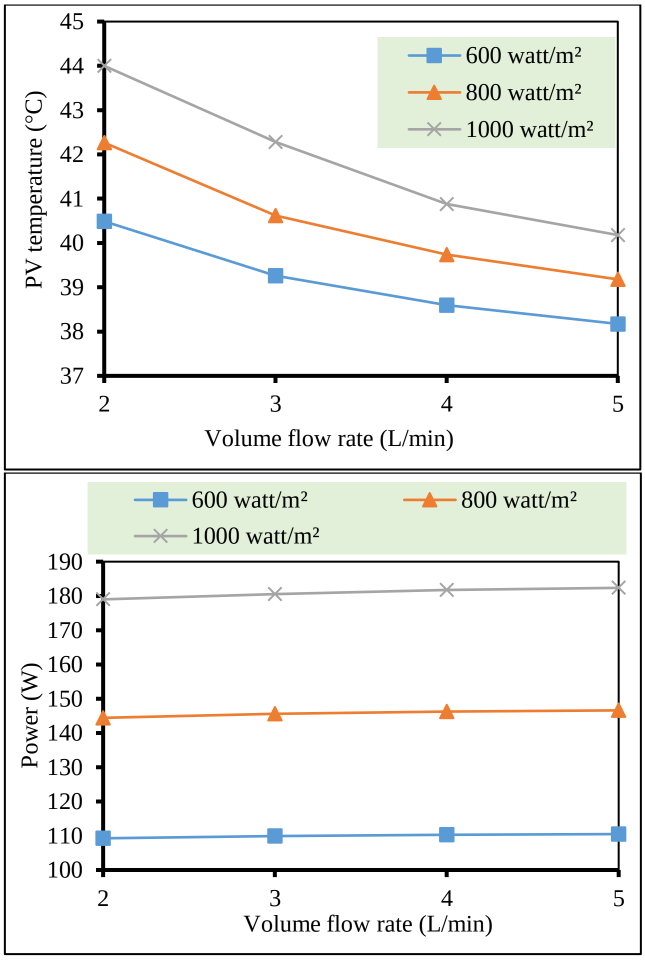

Figure 14. Variation of PV temperature and power production with water volume flow rate at different solar irradiance

The contour of temperature distribution of water over the panel surface at 800 W/m^2 solar irradiance, 40°C ambient temperature, and 35°C, at various water volume flow rates of 2, 3, 4, and 5 L/min, is shown in Figure 15. The variation range in PV surface temperature at a low flow rate is much higher than that of a high-volume flow rate, with the smallest variation being at 5 L/min volume flow.

The influence of varying water inlet temperature on PV power production and surface temperature at 40°C ambient temperature and 1000 W/m^2 solar irradiance is presented in Figure 16. The findings of this study indicated that the temperature of inlet water is the most influential factor in PV module temperature, as the lower water inlet temperatures and higher flow rate result in lower PV surface temperatures, higher power output, and improved efficiency. This maximization is due to lower inlet water temperatures and higher flow rates cool PV modules more effectively, reducing surface temperatures. This improves PV efficiency and power output by mitigating temperature-related performance losses. Thus, inlet water temperature is key to optimizing PV performance under high ambient temperatures and solar irradiance.

At a water temperature of 20°C, the optimal water flow rate for cooling the panel for maximum power production was found to be 5 L/min. This resulted in a peak power output of 192.69 W. However, at a rate of 2 L/min, the generated power was 188.63 Wt. Cooling the PV at 40°C water generated 175.58 W and 178.54 W, respectively, at 2 L/min and 5 L/min volume flow. The differences in power output are due to the varying effectiveness of heat removal; cooler water and higher flow rates dissipate heat more efficiently, maintaining optimal PV operating temperatures.

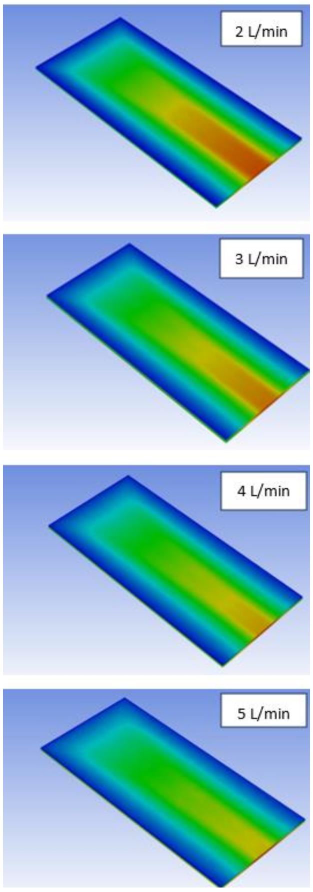

Figure 15. Variation in water temperature distribution at 800 W/m^2 solar irradiance at various flow rates

The temperature distribution contour of water over the panel surface at 20°C water inlet temperature and 1000 W/m^2 solar irradiance at various water volume flow rates of 2, 3, 4, and 5 L/min are shown in Figure 17, as shown in the figure by increasing the water volume flow rate while the water temperature was constant the water temperature deviation was decreased. So that increasing the water flow rate enhances heat transfer efficiency, leading to more uniform cooling across the panel surface and reducing temperature deviations.

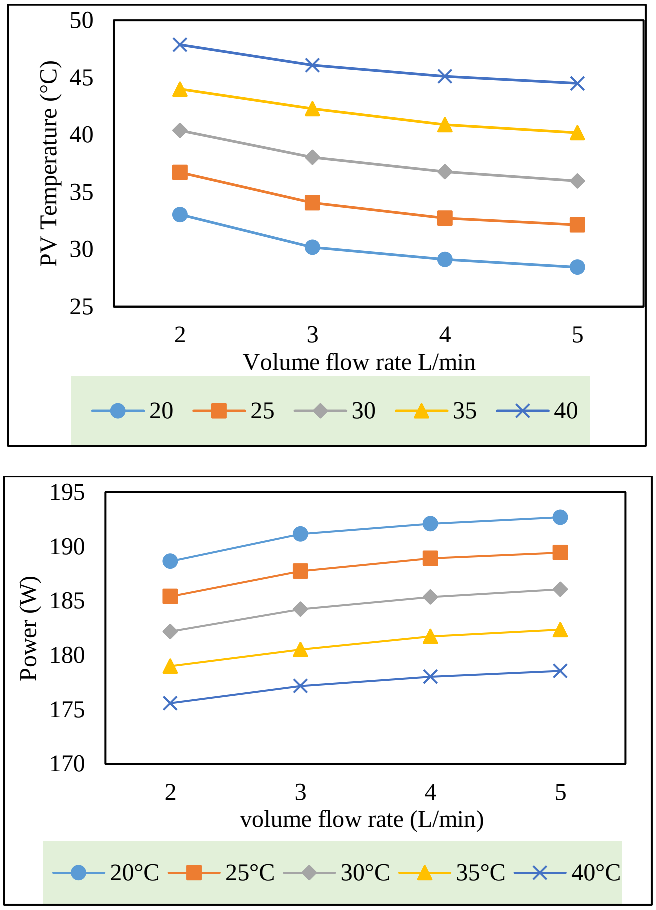

Figure 16. Variation of PV temperature and power production with different water volume flow rates at different water inlet temperatures

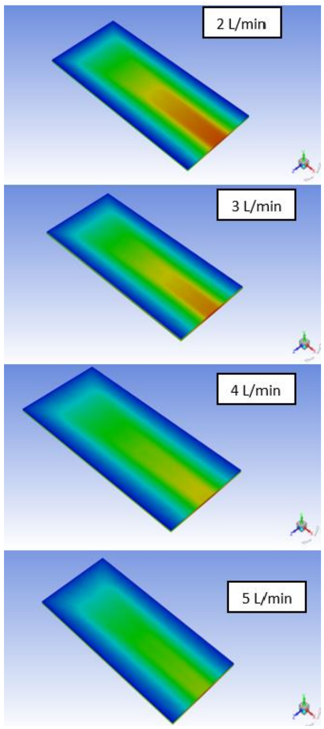

Figure 17. Variation in water distribution temperature at various flow and 20°C water inlet temperature & 1000 W/m^2 solar irradiance

Another key contribution from this study is the finding from the ANSYS simulation as it suggested that the solar radiation intensity is the most influential factor on the cooled PV panel power production. Also, increasing the water flow rate at a lower water inlet temperature can enhance the performance of the PV panel by decreasing its surface temperature and increasing the power output. Furthermore, the optimal water flow rate for cooling the panel for maximum power production was found to be 5 L/min at a water temperature of 20℃. This can be used to improve the efficiency of PV systems in hot climates.

4. CONCLUSIONS

This study demonstrated the integration of a combination the numerical simulations and experimental measurements to provide accurate and reliable results for determining the optimal water volume flow rate and cooling patterns for photovoltaic (PV) panels. Specifically, the ANSYS Fluent simulation was instrumental in assessing the impact of various parameters, such as ambient temperature, water inlet temperature, and solar radiation, on PV panel temperature and power production. The simulation reliably estimated the best water volume flow rate needed to achieve the desired panel temperature and power output. The results highlight the effectiveness of the three-side PV cooling system in improving panel performance. The flow rate of 5 L/min increased electrical efficiency by 20.25%, with boosting power output by 19.04%. This will provide a cost-effective alternative to traditional methods. The experimental test validated the simulation results with an error of 1.08%. The results also show minimal power losses during higher ambient temperatures, while significant in PV power output with increased solar irradiance and lower water inlet temperatures. In addition, the results showed that solar radiation intensity is the most critical factor, making high-irradiance regions ideal for deployment. Combining solar tracking systems with surface water flow rate and low-temperature cooling methods is highly recommended. Future studies should explore additional environmental factors, design optimizations, and evaluate economic feasibility.

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NOMENCLATURE

A	Area of the panel, m^2
FF	Fill factor
G	Incident solar radiation, W/m^2
I	Black body intensity, W/m^2
I_m	Maximum current, A
Isc	Short-circuit current, A
I_{mpp}	Maximum power point current, A
K	Coefficient of absorption
k	Thermal conductivity of solid W/m·K
L	Characteristic length, m
N	Number of readings
n_d	Day of the year
n	Refractive index
P_{PV}	PV power output, W
$P_{(enh.)}$	Enhanced power of PV
P_m	Maximum power, W
P_{ref}	Reference PV power output, W
Re	Reynolds numbers
$\vec{r}$	Position vector
$\vec{s}$	Direction vector
$\vec{s}'$	Scattering direction vector
T	Temperature, ℃
T_c	Cell temperature, ℃
t	Recorded time, min
V_f	Recorded volume, L
V_{in}	Inlet water velocity, m/s
V_m	Maximum voltage, V
V_{mpp}	Maximum power point voltage, V
V_{oc}	Open circuit voltage, V
V_w	Water volume flow rate, L/s
u	Velocity component in the x-direction, m/s
U	Velocity vector, m/s
g_x	Acceleration due to gravity in the x-direction, m/s^2
V_{wa}	Water velocity

V_{wi}	Wind speed	x_i	ith measurement value
$\bar{x}$	The average value of all of the readings taken for the X variable	Q	internal heat generation