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Research Article

Analyzing the effects of non-uniform cooling on solar panel performance

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ABSTRACT

Cooling solar panels improves their efficiency, performance, and power output, especially with increasing temperature. However, nonuniform cooling leads to temperature differences in solar panel cells, creating hot spots and thus degrading photovoltaic panel performance and reducing the lifespan of the panel. In this study, a practical experiment was conducted on three identical solar panels to compare their performance, where two panels were cooled via different methods and the third panel was not cooled. The first photovoltaic panel was completely cooled by passing water approximately uniformly. In contrast, the second panel was cooled nonuniformly by flowing the water path in the middle of the panel to achieve a nonuniform cooling process. The third panel was not cooled and was used as a conventional panel in factory conditions without any procedures. In addition, the three panels were mounted at a 25-degree angle towards the south. The results revealed that electrical power outputs of 38.5W, 35.6W, and 37.4W were achieved, with corresponding electrical efficiencies of 13.1%, 12.09%, and 12.7% for the uniformly cooled panel, the uncooled panel, and the non-uniformly cooled panel, respectively. These findings indicate that the uniformly cooled panel achieved the highest performance improvement, with an 8% increase compared to the conventional uncooled panel. However, this improvement decreased by 3% in the case of the non-uniformly cooled panel. This improvement indicates that irregular cooling should be highlighted, as well as its influence on the performance of the solar panel. Therefore, to achieve optimal electrical performance while preventing the formation of hot spots, it is essential to ensure uniform cooling.

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INTRODUCTION

Recently, solar energy systems have gained increasing attention [1–3] due to their numerous advantages, including being environmentally friendly, inexhaustible, and the sources of renewable energy [4–6]. The photovoltaic solar energy system uses photovoltaic devices to convert sunlight into electricity. The production of photovoltaic panels faces several challenges, including high panel temperatures resulting from intense solar radiation and the scorching summer climate in Iraq [7, 8]. Agreed with earlier research indicating that solar panels function more efficiently at

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reduced temperatures [9, 10]. In real-world applications, however, environmental variables such as accumulated dust, avian fouling, and shadows cast by adjacent structures frequently trigger hotspot development [11], severely degrading the overall electrical yield. The detrimental impacts of this partial shading can be controlled either by altering the connection of the photovoltaic cell array through various photovoltaic configurations [11, 12] or by integrating maximum power point tracking (MPPT) technologies [13]. Operating heat remains a fundamental parameter dictating electrical output. In fact, upwards of 80% of the solar radiation incident upon the panels is lost as thermal energy rather than being converted into useful current [14]. Escalating module temperatures inevitably depress the open-circuit voltage (V_{oc}) alongside total power generation; although the short-circuit current (I_{sc}) sees a marginal lift, the net consequence is a sharp drop in conversion efficiency and a heightened risk of permanent material damage [15]. To solve this problem a cooling system should be installed in case of intense solar exposure and high temperatures. Standard practices for regulating cell climates and recovering efficiency generally rely on forced air or fluid-based heat extraction [16]. Water is a more effective coolant than other substances, so it is important for the thermal regulation of solar panels. However, an uneven distribution of temperatures may result from the liquid cooling technique. This causes each cell to operate at a different electrical efficiency, thereby the total current of the series of connected cells in the photovoltaic module to be limited by the lowest current produced by the cell at the hotspot [17]. The temperature variation on the surface of both concentrated and non-concentrated photovoltaic systems is due primarily to uneven illumination, leading to degradation and increased wear of solar cells. Consequently, it affects the electrical efficiency of the cooled solar panel due to the appearance of hotspots. The formation of hotspots on the surface of PV modules is a common occurrence and significantly contributes to substantial power loss within the module while also reducing the lifespan of the panel [18].

Radziemska [19], investigated the impact of temperature on PV panel electrical characteristics. The results indicated that when the solar cell temperature increased, electrical efficiency decreased by -0.08%/K. Chander et al. [20], reduce the influence of the cell temperature on PV parameters. It was found that the relative change occurred from -0.0022/°C to -0.002/°C, -0.0025/°C, -0.0022/°C, and -0.013/°C for electrical power, short-circuit current, open-circuit voltage, and fill factor, respectively. Zaoui et al. [21], conducted both experimental and numerical studies to investigate the effect of temperature on solar panel performance. The data show a 54.54% decrease in electrical output as the temperature increases from 25°C to 100°C. Salem et al. [22], investigated the influence of water cooling on solar panel performance. The results indicated that the electrical efficiency of the cooled panel increased by 8% when compared to the uncooled panel. Jaffar et al. [23], cooled a solar panel using air to investigate the effect of higher temperature on solar panel performance. They observed that boosting the air velocity reduces the temperature of the photovoltaic unit, resulting in a 17% improvement in electrical efficiency. Raja et al. [24], suggested a closed-loop water cooling system for solar panels to examine the effect of rising temperature on solar panel performance. the results indicated a 72% enhancement in output with an even heat distribution across the solar panel, thereby reducing the impact of hot spots. Hadipour et al. [25], developed a pulsed spray water cooling device for PV panels to investigate the effect of increasing temperature on solar panel performance. The results showed an increase in electrical power production of 33.3% with steady-spray cooling and 27.7% and 25.9% with pulsed-spray cooling at duty cycles of 1 and 0.2, respectively, as compared to non-cooled panels. Muslim et al. [26], cooled three solar panels with water, with water flow angles of 60°, 30°, and 0° for the first, second, and third panels, respectively, to evaluate the effect of increasing temperature on solar panel performance. Compared to the uncooled module, the electrical efficiency of the first, second, and third modules increased by 17%, 15.3%, and 13.6%, respectively. Nabil and Mansour [27], studied four techniques for cooling solar panels to examine how increased temperature affects the performance of the solar panel. The findings indicated that the water cooling method implemented on the frontal surface of the photovoltaic module was the most effective in terms of electrical efficiency by 6.84% and dissipating heat by 29.37%. Shalaby et al. [7], tested two identical photovoltaic units simultaneously to assess the effect of temperature increase on the solar panel's performance. One cooled with water from the back and the other uncooled. The findings indicate that the power output of the cooled panel ascended by 14.1%, thereby increasing its efficiency. Murugan et al. [28], investigated the performance of solar panels under uniform cooling by employing air cooling and various airspeed control techniques. The results showed that temperature changes of 1.5°C to 2.5°C lead to efficiency improvements of 17% to 22%. Baloch et al. [29], performed an experimental and computational study to investigate the effect of uniform cooling on the performance of solar panels. The results demonstrated a 35.5% augmentation in the output power with uniform cooling compared with that of the panel without cooling. Al Tarabsheh et al. [30], investigated the cooling processes of three solar panels using a variety of methodologies to determine the influence of consistent temperature distribution on solar panel performance. The results showed that the panel with the most uniform temperature distribution exhibited the highest efficiency gain (17%). Arifin et al. [31], used aluminium heat sinks to cool down the temperature of a solar panel. Results showed that average panel temperature decreased from 85.3 °C to 72.8 °C with 18.67% increase in electrical output. Zhu et al. [32], conducted a study on cooling photovoltaic panels through water immersion. The results showed that the temperature

remained uniform; however, the electrical performance of the cell unit deteriorated after prolonged use. Li et al. [33], examined the radiative cooling methodology for solar panels over the fall and summer seasons using an improved method to investigate the influence of cooling on solar panel performance. The new cooling approach resulted in an increase in electricity efficiency of 1.69% in the summer and 1.51% in the fall. Nižetić et al. [34], experimentally investigated the effect of spray cooling on solar panel performance. The results revealed an increase in the electrical output of the photovoltaic panel to 16.3%. Yusoff et al. [35], experimentally used water cooling on the solar panel by using a fan in one case and a water pump in another and compared both cases with an uncooled panel to investigate the impact of cooling on the performance of the solar panel. The experimental results indicated that the electrical power increased by 38.98% for the water pump cooling while for the fan cooling the increase was 32.23%. Panda et al. [36], conducted a comparison between front-surface cooling and back-surface cooling of a PV panel to study the relationship between temperature rise and the solar panel's performance. The results revealed a decrease in temperature for both cases, with a 28.6% increase in electrical power generation, with a slight advantage for front-surface cooling. Amanlou et al. [37], cooled a solar panel by ensuring a uniform distribution of airflow to study the effect of temperature on the performance of the solar panel. The results revealed that with an increase in the airflow rate, the electrical efficiency improved by 13.5%. Agyekum et al. [38], compared a rear-cooled solar panel with an uncooled panel to study the effect of cooling on solar panel performance. The results showed an 11.9% increase in electrical efficiency compared to the uncooled panel. Haidar et al. [39], studied an improved method using the principle of evaporative cooling on a photovoltaic panel to study the effect of increased temperature on the performance of the solar panel. The results revealed more uniform temperatures with a 5% improvement in the generated power. Hasan et al. [40], investigated the effect of rear-surface cooling on a photovoltaic panel using water and compared their findings to those of an uncooled panel to determine the influence of cooling on solar panel performance. The data showed an improvement in the mean electrical efficiency of the panel of approximately 20.8%. Bahaidarah et al. [41], conducted computational and experimental research to find the impact of cooling on the efficiency of solar panels. Results showed that the temperature decreased and the efficiency increased by 9%. Basrawi et al. [42], studied the effect of two water-cooling conditions on a solar panel surface to assess the impact of different cooling methods on the efficiency of solar panels. Comparison results showed an improvement of 6.10% and 13.50% in electrical performance for the half-surface and full-surface cooling settings respectively in comparison with the uncooled panel. Sornek et al. [43], created and thoroughly evaluated a water-cooling system designed to improve the performance of solar panels, so as to study how cooling affects their efficiency. The data clearly showed a significant increase in average output power up to 10.3%.

Earlier research assumed that their cooling was evenly distributed, and previous studies used cooling and saw performance gains. However, in practice the cooling was not uniform enough and this indicates there is still room for improvement in the electrical performance. This shows how important it is to optimize cooling techniques so that PV modules can be made as efficient as possible. Where the literature did not address the issue of non-uniform cooling variations and their impact on the solar electrical performance. Hence, in this extensive study, a detailed experimental study was carried out in Baghdad, Iraq. The three solar panels were: the first panel (PV1) was uniformly cooled, the second panel (PV2) was non-cooled and the third panel (PV3) was non-uniformly cooled. The coolant was water. A detailed comparative study of the three panels was carried out to demonstrate in detail the effect of non-uniform cooling on the electrical performance of the PV modules.

MATERIALS AND METHODS

The practical experiment was undertaken on 26 April 2024 in Baghdad, Iraq. During the practical experiment, three Hs-1850 solar panels were used: one uncooled and the other two cooled using different methods. The experiment was conducted out of doors with equal temperature and solar radiation conditions for all panels. All three panels were measured simultaneously on 26 April 2024 from 9:00 AM to 3:00 PM. The temperature started at 32 °C at 9:00 A.M and gradually increased to 37 °C by 3:00 P.M, while the solar radiation ranged from 631 w/m² to 904 w/m².

Experimental Setup

In this detailed experiment, three solar panels were tested: two were cooled via distinct methods with water as the cooling fluid, and one was uncooled. The three solar panels were compared in terms of key operational performance indicators such as electrical power output and efficiency for each panel, all under identical and controlled environmental conditions simultaneously.

A uniformly cooled solar panel (PV1) was achieved by placing an acrylic sheet (dimensions 700×420 mm, thickness 2 mm) at the rear of the panel, as indicated in Figure 1(A). When water flows through the cooling chamber, it directly contacts the rear of the panel, allowing efficient heat transfer to the PV panel without insulation. The interior structural edges of the solar panel were filled with silicone in the spaces between the rear surface of the solar panel and the aluminium frame, and in the corners. This was done so that water would not leak from the edges to the outside or to the internal components of the solar panel that could cause potential damage. The acrylic sheet was fixed in place using silicone on the rear peripheral edge of the PV and screws. Water was introduced into the solar panel

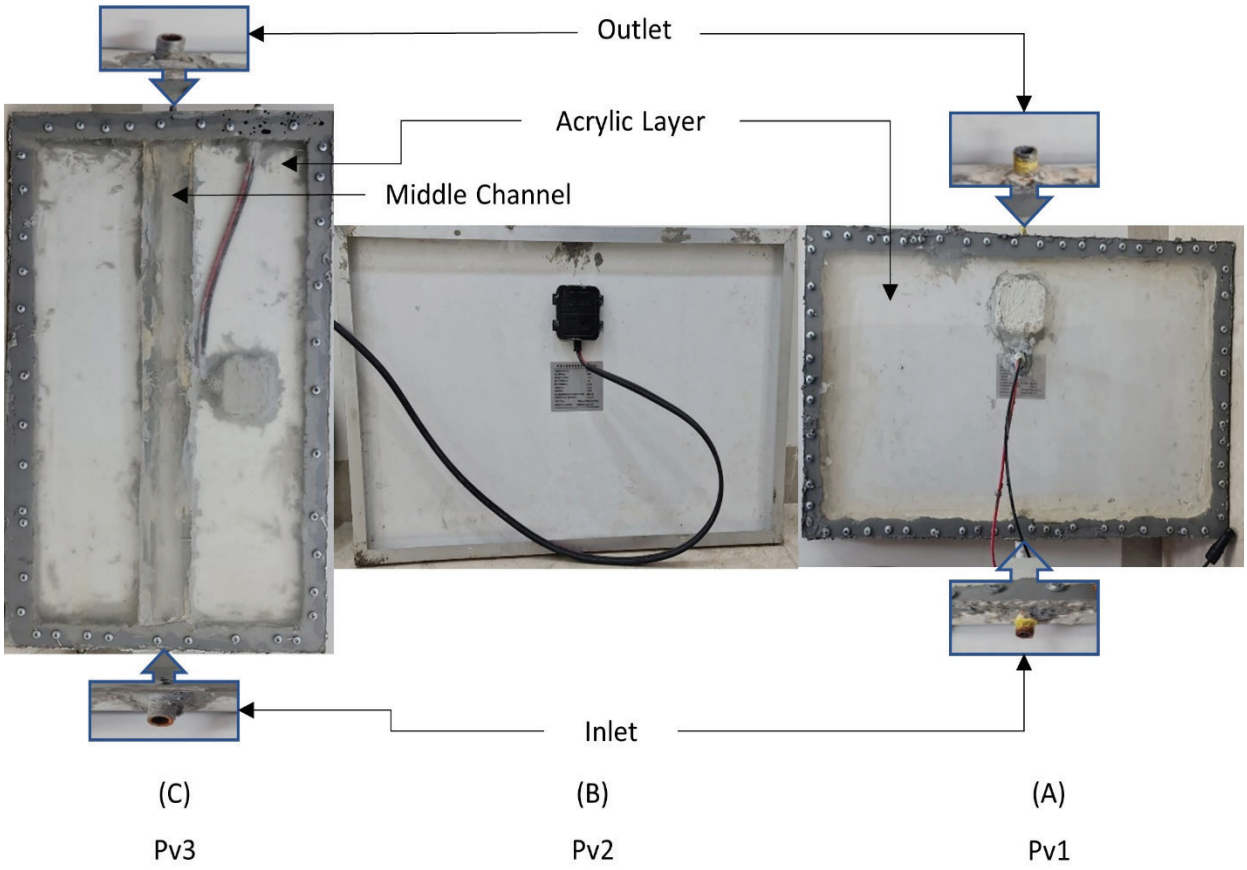

Figure 1. Experimental setup modules (A) Uniformly cooled PV1 (B) Conventional panel PV2 (C) Non-uniformly cooled panel PV3.

by creating two precisely measured 10 mm diameter holes in the aluminium frame of the panel: one in the middle of the top part and the other in the middle of the bottom part. In each opening for water in-flow and out-flow a tube was inserted. The electrical wiring was attached to the clearly marked positive and negative terminals in the junction box of the panel. The junction box was sealed with a durable rubber gasket, and silicone was applied around the edges. It was completely sealed to prevent water from leaking into the internal connections of the PV panel that could cause serious electrical damage. The connecting wires were pulled out from the bottom of the acrylic sheet at the center position. Insulating tube and silicone were used to prevent leakage. Notably, the panel (PV1) was placed horizontally during the experiment.

The conventional, uncooled solar panel (PV2) was not cooled, and according to standardised testing conditions, it was subjected to the influence of various environmental factors. As indicated in Figure 1(B), no additional cooling element was added to the panel. Only the electrical wires were connected to the clearly designated negative and positive terminals of the solar panel, which were located in the panel's junction box. The box was securely sealed via a durable rubber gasket, with a thin protective layer of silicone applied around its edges to protect against external environmental influences that could damage the sensitive internal components of the photovoltaic panel. Notably, the panel (PV2) was placed horizontally during the experiment.

The nonuniformly cooled panel (PV3) in Figure 1(C) was created by constructing a water channel in the middle of the back of the panel, which was made of acrylic with a height of 23 mm and a width of the photovoltaic cell in the middle of the PV panel, extending along the entire of the PV panel. An acrylic sheet matching the dimensions of the water channel was placed over the channel walls. The channel parts were securely fixed via adhesive and silicone, and the channel was then affixed to the back surface of the PV via adhesive and silicone. The channel walls were 680 mm long to ensure that water exited the channel and adequately filled the entire panel with water, whereas the channel cover was the full length of the PV (700 mm). The function of the water channel was to create more varied temperatures across the solar cells, ensuring that water circulation through the channel was more effective. Silicone was applied along the inner sealing edges of the photovoltaic panel, particularly between the back of the PV and the aluminium frame, as well as in the corners. This was to prevent water from leaking through the edges either to

the outside or into the sensitive internal components of the solar panel where it could cause damage. Another acrylic sheet with dimensions of 700×420 mm was securely fixed at the back of the panel via silicone and screws. Two 10 mm diameter holes were made in the aluminium frame of the panel, one in the middle of the top part and the other in the middle of the bottom part, ensuring that water flowed through the channel and exited from the other side. Each opening had a tube attached for water to flow in and out. The electrical wires were connected to the positive and negative terminals of the solar panel, which are located in the panel's junction box, a critical component of the solar panel that requires complete protection. Put a durable rubber gasket around the edges of the junction box. Put silicone around the edges and covered the whole box with silicone. This was to prevent water from leaking into the box and damaging the sensitive internal circuitry of the solar panel or causing an electrical short that could result in a loss of energy and inaccurate readings from measuring devices. A hole of 16 mm in diameter was also made at the upper-left corner of the aluminium frame for the wire exit. An insulating tube for the wires and silicone were used to avoid leakage. Additionally, the panel (PV3) was placed vertically during the experiment.

Figure 2 clearly illustrates the comprehensive complete cooling system for three solar panels installed on a sturdy metal frame oriented due south at 180 degrees. Additionally, the space under the panels and all the objects behind them are covered with a white reflecting cloth. The lower of this white cloth was periodically wet with water during the measurements. This is a strategic process to reduce unwanted thermal emissions from the ground and objects around, allowing the minimization of heat reflected from the ground by the thermal camera. This guarantees that the images acquired by the thermal camera only show temperature differences due to the solar panels and not due to external environmental factors. Consequently, this significantly enhances the clarity and accuracy of the images in the thermal camera and provides valuable insight investigate the cooling performance of PV, thus rendering the comparison results more scientifically reliable.

Figure 3 clearly illustrates the detailed experimental setup with precisely calibrated measuring devices, which include a high-resolution thermal camera, a digital power meter (PV200), a specialised Solar Survey 200R, a portable dedicated mobile computer and a dedicated computer for real-time data collection. The three solar panels are securely affixed on a robust metal stand at an angle of 25 degrees, which is the theoretically determined optimal tilt angle in May to achieve the highest possible solar irradiance and, consequently, the highest efficiency [44]. The integrated cooling system includes a durable water pump, a water tank, and efficiently arranged pipes. The pump continuously circulates water through the strategically designed cooling chambers of the panels.

The solar panels used in this experiment are HS-1850 type and are monocrystalline panels. Each panel consists of 9 rows and 4 columns of cells, of manufactured medium dimensions exactly 700×420×25 mm. Table 1 shows the



Figure 2. Experimental setup panels.

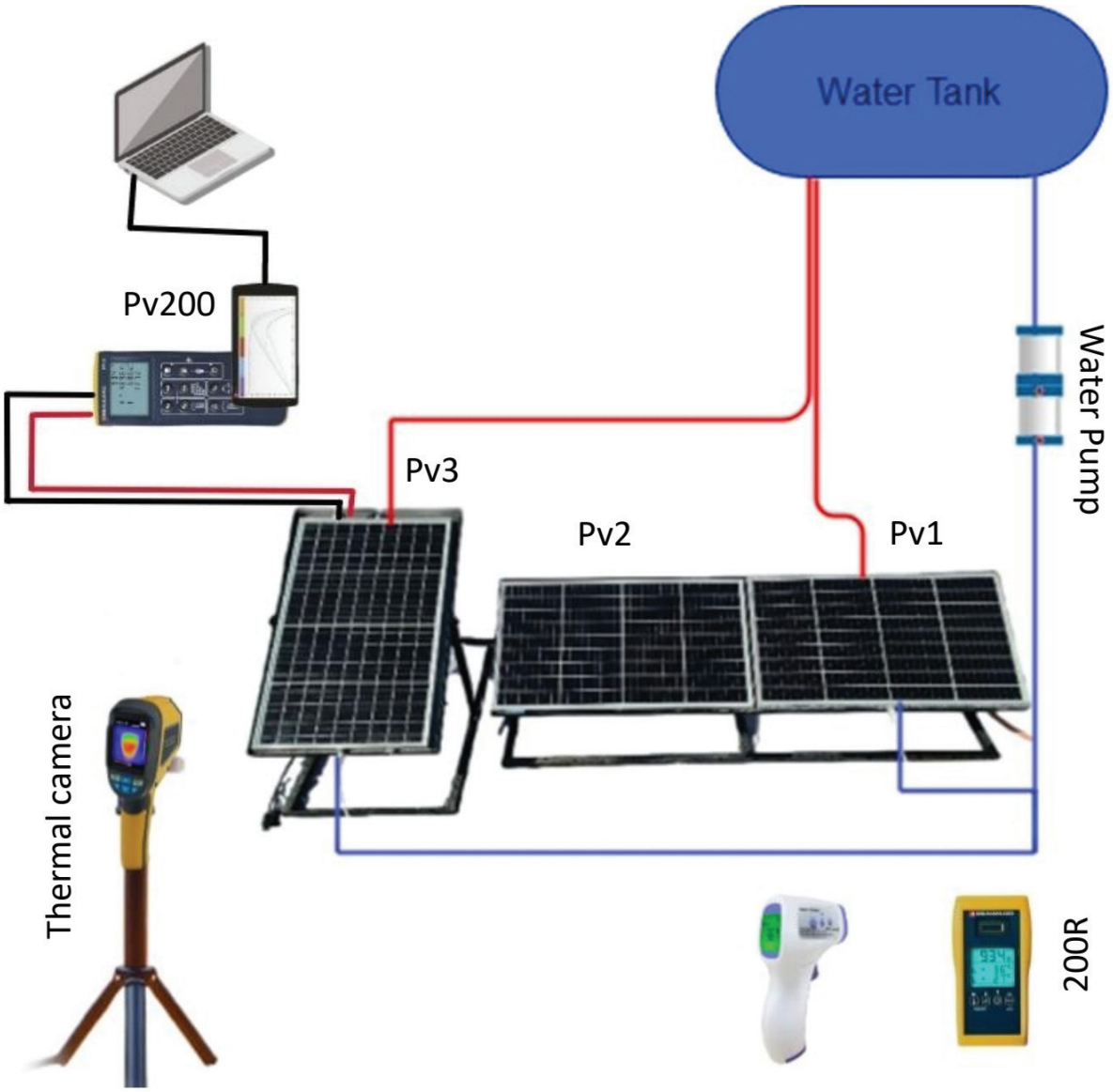

Figure 3. Schematic of the experimental system.

Table 1. Electrical data of the photovoltaic module at a cell temperature of 25 °C, and 1,000 W/m^2

Specifications for Photovoltaic Module							
Model	**Maximum power**	**Maximum Voltage**	**Maximum Current**	**Open-Circuit Voltage**	**Short-Circuit Current**	**Number of Cells**	**Dimensions of module**
HS-1850	50W	18V	2.78A	21.8V	3.02A	36 (4×9)	(700×420×25) mm

panel specifications in details like current, voltage, electrical power and other important parameters.

The PV 200 device was used to accurately analyse the specifications of the photovoltaic unit; it is a precise and user-friendly electronic device designed to thoroughly test the performance of photovoltaic cells and generate detailed IV and PV curves. The device supports advanced NFC wireless communication, allowing real-time data read by the device to be transferred to a compatible mobile phone. Measurements of the open-circuit voltage, electrical power, short-circuit current, PV and IV curves were recorded via NFC technology and then transferred to a dedicated computer.

The solar irradiance and tilt angle of the panels were precisely measured via a highly advanced Solar Survey 200R device, which is equipped with an integrated digital inclinometer for measuring surface tilt and a high-accuracy compass for determining surface orientation. The 200R device connects wirelessly with the PV200 device, allowing instantaneous data read by the Solar Survey 200R to be transferred to the PV200.

The temperature of the solar panels was measured via two highly reliable methods. The first method involves a handheld infrared thermal camera, identified as an HT-02D, which converts thermal energy (heat emissions) into visible light to precisely inspect a specific target. It captures high-resolution thermal images, which are stored on an SD card that is inserted into the camera. The second method uses a non-contact laser temperature gun, which is an infrared thermometer (HG01) that allows the surface heat distribution temperature to be measured from a distance of 3–5 cm without making physical contact with the object being measured. It is positioned in front of the selected cell whose temperature is to be measured, enabling the accurate temperature of each individual cell to be recorded individually.

Formula Analysis

The impact of temperature fluctuations significantly affects both the electrical energy production and the operational efficiency of solar panels. Elevated temperatures cause to a notable decrease in both electrical power production and overall efficiency. Understanding this critical dynamic is crucial for improving solar energy systems. Equation (1) shows a direct relationship between the cell temperature (T_C)and the electrical power (P) [45]:

$$P = G_T \tau_{pv} \eta_{T_{ref}} A [1 - 0.0045(T_C - T_{ref})] \quad (1)$$

where η_{Tref} represents the photovoltaic module's electrical efficiency at the standard reference temperature T_{ref} and G_T represent the incident solar radiation flux (irradiance) on the module surface (W/m^2), τ_{pv} represents the transmittance of the solar cell's outer layers, T_C represents the operating temperature of cell/module, and A represents the aperture surface area of the PV module (m^2).

Similarly, there is a proportional linear relationship between the temperature of the cell (T_C) and the electrical efficiency (η_{ele}) [46]:

$$\eta_{ele} = \eta_{T_{ref}} [1 - \beta_{ref} (T_C - T_{ref})] \quad (2)$$

where β_{ref} is the coefficient of temperature, The manufacturer of PV module normally gives precise values for η_{Tref} and β_{ref}.

The overall performance of the solar panel is influenced by its electrical efficiency (η_{ele}), Which is defined as the ratio of the generated electrical output power to the incident radiation on its surface area [47]:

$$P_{out} = V_{mp} * I_{mp} \quad (3)$$

where P_{out} represents the power output of the photovoltaic module, I_{mp} (Ampere) and V_{mp} (Volt) are the maximum current and voltage values, respectively, at the maximum output power.

$$P_{in} = G_T * A \quad (4)$$

where G_T represents radiation (w/m^2) and where A represents the area photovoltaic of module(m^2). Therefore, the electrical efficiency can be accurately obtained according to the following equation:

$$\eta_{ele} = \frac{P_{out}}{P_{in}} \quad (5)$$

Uncertainty Analysis

The analysis of measurement errors involves the systematic study and quantitative evaluation of measurement uncertainty. Errors are the discrepancies between the measured values and actual values. Because the true value is rarely known with absolute precision, the exact error magnitude remains unknown. However, on the basis of the information available, the error range is confined to a specific interval, either plus or minus the given value. In experimental research, there is often no precise determination of the accuracy of recorded data. As a result, an uncertainty analysis of the measuring instruments used should be performed to quantify the accuracy of the experimental result. The reliability of the experimental findings is contingent upon both the precision of the measurement devices and the potential for human error. Table 2 shows the percentage error values of the measuring devices used in the experiment.

In accordance with Holman and Gajda's [48] error analysis technique, the percentage error of the PV electrical efficiency may be calculated as follows:

$$\frac{W_\eta}{\eta} = \left[\left(\frac{W_I}{I}\right)^2 + \left(\frac{W_V}{V}\right)^2 + \left(-\frac{W_G}{G}\right)^2\right]^{1/2} \quad (6)$$

Table 2. Measurement device uncertainties

Parameter	Time	Solar radiation	C urrent	Voltage	Temperature measurement
Accuracy	2%	5%	± (1% + 2 digits)	± (0.5% + 2 digits)	± 2%

where W_η is the uncertainty in the electrical efficiency, W_I is uncertainties in current ($W_I = \frac{V_{mp}}{G \times A}$), W_V is uncertainties in voltage ($W_V = \frac{I_{mp}}{G \times A}$) and W_G is uncertainties in radiation ($W_G = -\frac{V_{mp} \times I_{mp}}{G^2 \times A}$). In the context of evaluating solar panel performance, it is essential to assess the uncertainty associated with various parameters to accurately determine electrical efficiency through the following key components: output voltage, solar irradiance, and the current generated by the PV. Each of these parameters has inherent uncertainty, which arises from measurement errors, instrument limitations, and environmental influences.

By incorporating the error values presented in Table 2 for the current, voltage, and solar irradiance from the measuring devices in Equation (6), the overall uncertainty in electrical efficiency can be systematically calculated:

$$\frac{W\eta}{\eta} = \sqrt{(0.01)^2 + (0.005)^2 + (-0.05)^2}$$
$$\frac{W\eta}{\eta} = 0.05123 = 5.123\ \% \quad (7)$$

RESULTS AND DISCUSSION

In the conducted experiment, three photovoltaic panels were subjected to performance tested: two were cooled via different water-based methods, and the third panel remained uncooled. The three solar panels were oriented southwards with a fixed tilt angle of 25 degrees. Water pipes were connected to the cooling systems of both the PV1 and PV3 panels, and testing took held between 9:00 A.M and 3:00 P.M. Solar radiation and Ambient temperature were recorded hourly using the Seaward 200R device, while electrical parameters were measured each hour by connecting the PV200 device to each panel individually. Thermal images were taken every hour with a vertical thermal camera with a white cloth sprayed before to improve the image clarity and accuracy. All recorded data were then transferred to a computer for analysis, and the results were categorised into thermal and electrical aspects.

Thermal Image Analysis

Thermal analysis of photovoltaic panels was performed with a high resolution thermal camera and detailed thermal images were recorded for each solar panel. These thermal images illustrate a clear thermal gradient from blue (coolest) to white (hottest).

The first solar panel (PV1) with uniform cooling in horizontal direction shows non-uniform temperature distribution over the cells with the gradient from bottom to top. The bottom part of the panel is cooler than the top part. The edges on both left and right are hotter than the middle. This can be attributed to the inflow of water into the cooling chamber from the centre of the lower section and its exit from the centre of the upper section of the PV. As a result, the water is at its coolest at the entry point and gradually heats up as it rises due to Heat transfer between the water and the back surface of the PV, as well as at the edges. Additionally, the central upper section of the photovoltaic

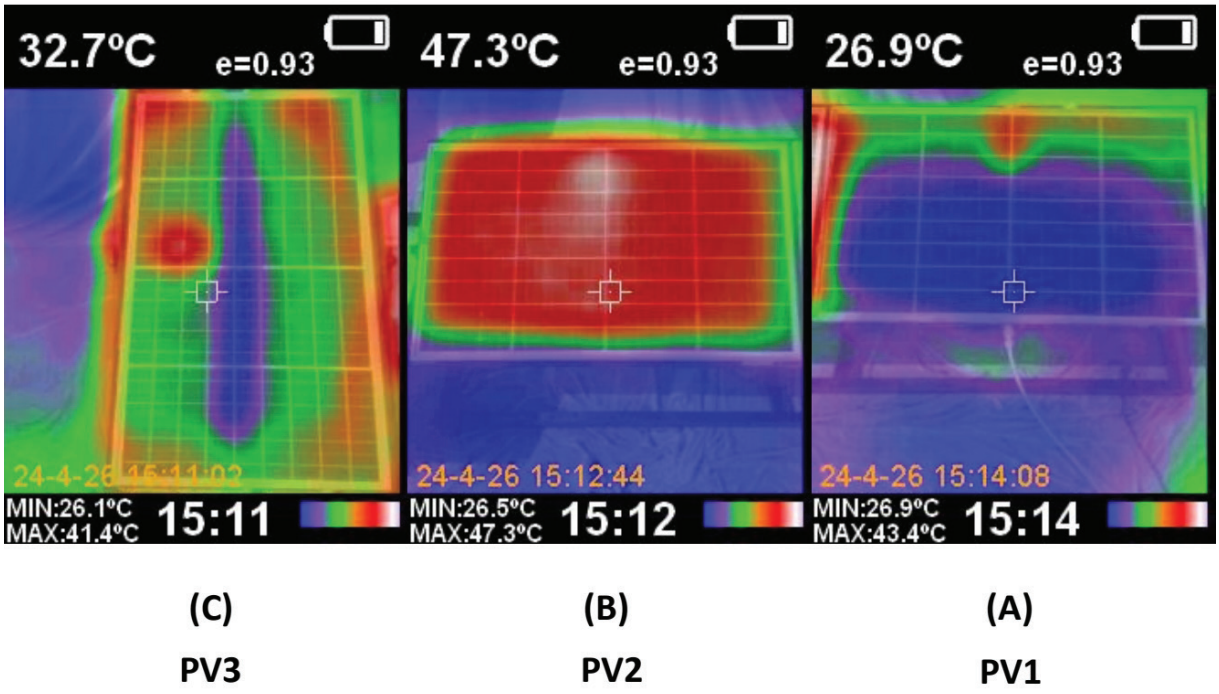

Figure 4. Thermal images for three panels.

panel has the highest temperature, which is caused by the heat from the electrical junction box located in this area, as illustrated in Figure 4(a).

The second conventional panel (PV2), which was not cooled, shows uniformly high temperatures throughout, with the central top area being notably hot due to the heat from the panel's junction box located in this section, as shown in Figure 4(b).

For the third panel (PV3), which is nonuniformly cooled vertically, there is significant temperature irregularity; the middle of the photovoltaic panel is cooler than the edges, creating a thermal gradient from the centre towards the sides. This significant temperature gradient occurred due to the addition of a central water channel at the back of the panel, which helps to minimise the flow of water towards the panel's edges as much as possible. As a result, the cooling process becomes more controlled and directed, reducing temperature variations across the panel. Furthermore, a red-coloured circle, representing the hottest point, can be observed on the left side of the panel, caused by the heat from the PV panel's junction box in this region, as illustrated in Figure 4(c).

Electrical Experimental Analysis

Several factors influence a panel's efficiency, including ambient temperature, solar radiation level, panel tilt angle, and orientation. In this study, the tilt angle was fixed at 25 degrees facing south. Consequently, the main factors affecting solar panel efficiency are radiation and ambient temperature. During the experiment, the temperature of each panel was measured via a thermal camera, and the amount of solar radiation was measured via a Solar Survey 200R device. Additionally, the electrical power output was calculated via a seaward PV200 device, therefore influencing the electrical efficiency of the solar panel.

Figure 5 shows Changes in ambient temperature and solar radiation during the daytime from 9 a.m. to 3 p.m. The graph shows that at 9 AM the ambient temperature and radiation started to increase gradually. The radiation gets to its peak at about 12 PM, midday, which shows the highest level of radiation throughout the day. This peak occurs when the sun is at its zenith, giving the most exposure to the sun rays. The solar radiation starts to decrease after 12 PM, whereas the ambient temperature keeps increasing and reaches its maximum values between 1 PM and 3 PM. The increase in ambient temperature, despite the decrease in radiation afternoon, may be attributed to the time it takes for the Earth and its surroundings to absorb heat.

As evidenced by the results, the electrical output power shown in Figure 6 highlights the superiority of the approximately uniformly cooled panel. The average daily electrical power output was recorded as 38.5W for PV1, 35.6W for PV2, and 37.4W for PV3. Accordingly, a comparative analysis was conducted among the three panels in terms of electrical power generation, leading to the following findings: an improvement of approximately 8% was observed when the uniform cooled panel (PV1) was compared with the conventional noncooled panel (PV2). This improvement underscores the significant effectiveness of cooling methods in enhancing electrical energy production. Additionally, a nearly 5% improvement was noted when comparing the nonuniformly cooled panel (PV3) with the noncooled panel (PV2) in the middle, indicating that the cooling method also increased the electrical output compared with the conventional panel. Furthermore, when the PV1 was compared with the PV3, the improvement in PV1 was 3%. This finding underscores that cooling methods do not yield the same electrical performance. Specifically, the electrical performance decreased by 3% due to increased thermal variation within the photovoltaic module, as

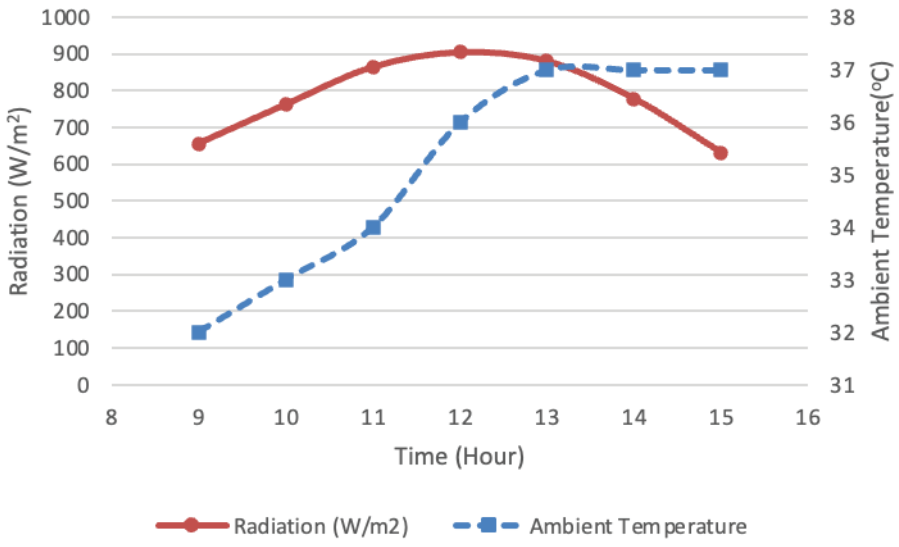

Figure 5. Ambient temperature and solar radiation at different times.

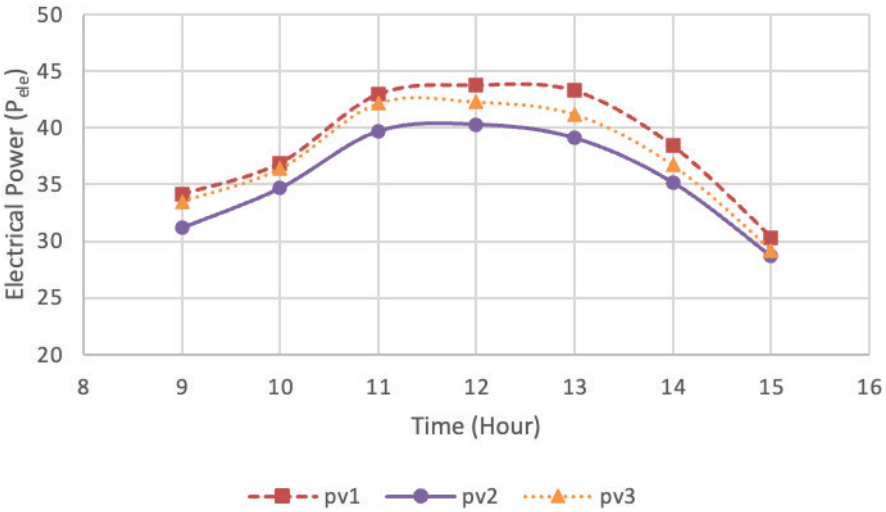

Figure 6. Comparison of the three panels in regarding of electrical power output.

illustrated in Figure 4c. As a result, the non-uniform cooling led to a reduction in the panel's electrical output power.

The results show that water cooling increases the electrical output of the solar panel, with the greatest improvement noted in the PV1 compared with both the noncooled panel and PV3 panel. Although both the first (PV1) and third (PV3) panels are water-cooled, the first panel presented a better energy output because of a lower thermal gradient across the cells, as illustrated in Figure 4a, whereas the third panel (PV3) presented a significantly greater thermal gradient, as illustrated in Figure 4c. This thermal gradient has led to a reduction in power output due to its impact on the series current of the solar panel. The total current produced by the panel is limited by the lowest current produced by the cell at the hot spot. Additionally, it decreases the panel's voltage, as an increase in temperature reduces the bandgap energy of the semiconductor material due to the increased atomic spacing, thereby lowering the generated voltage. Since both current and voltage directly influence the electrical power output of the panel, as described by Equation (3), this effect becomes a critical factor in overall performance. It is also obvious that solar radiation influences the electrical output of a photovoltaic panel, with peak solar radiation producing the most energy.

As shown in Figure 7, the average electrical efficiency of the solar panels during the test day was 13.1%, 12.09%, and 12.7% for PV1, PV2, and PV3, respectively. These results emphasize the differences in the efficiency of the

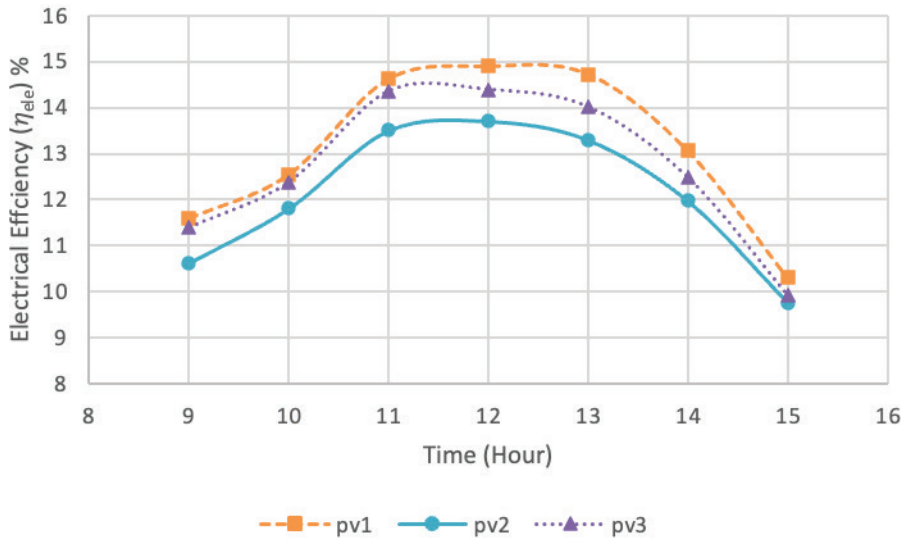

Figure 7. Comparison of the electrical efficiency of the three panels.

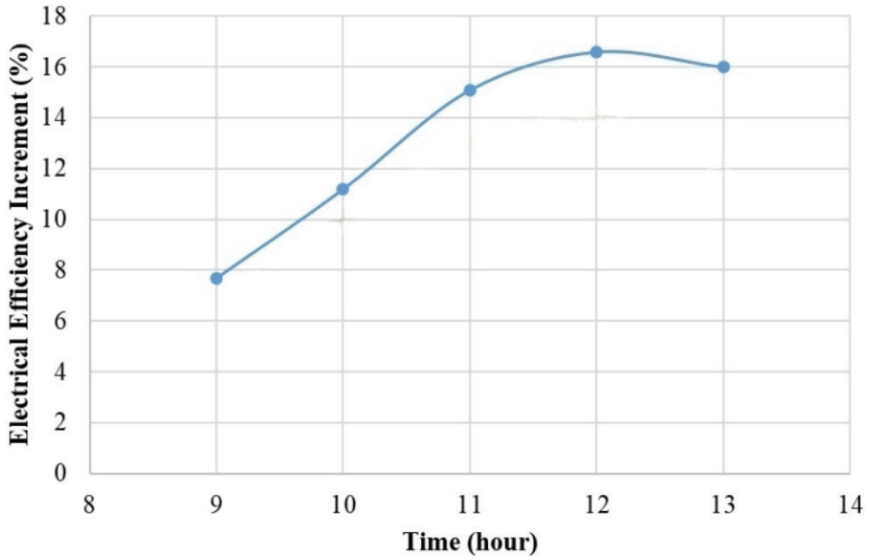

Figure 8. Electrical efficiency at different times [26]. Adapted from: Muslim N, Ghadhban S, Hilal K. Enhancement of solar photovoltaic module performance by using a water-cooling chamber for climatic conditions of Iraq. Int J Renew Energy Res. 2020. Available at: https://ijrer.org/index.php/ijrer/article/view/10937

tested panels. As seen in Figure 7 the electrical efficiency enhancement of PV1 is about 8% as compared to PV2. This means that a solar panel is much more efficient under the same environmental conditions if it is cooled. Likewise, the third cooled panel (PV3) showed an efficiency increase of around 5% compared to the second uncooled photovoltaic panel. The results indicate that independently of the cooling technology applied, cooling significantly improves solar PV panels electrical efficiency. PV1 also has an electrical efficiency 3% higher than PV3. The electrical efficiency of PV1 improved due to the lower thermal gradient compared to PV3, as shown in Figure 4. The thermal gradient of PV3 is higher, so the negative effects of heat on efficiency are reduced. We can observe that the first cooled panel (PV1) reaches the highest electrical efficiency thanks to a lower thermal gradient in comparison to the third cooled panel (PV3), which shows a notably higher thermal gradient. Thus, the electrical power output of the solar panel is negatively affected by the thermal gradient. Therefore, electrical efficiency is lowered. The electrical efficiency is given by Equation (5) and is directly proportional to the panel power output. So loss of power generation is directly a loss of the total efficiency.

Furthermore, the efficiency of PV is greatly influenced by temperature. It shows the significant influence of temperature on the PV, because the electrical efficiency of the three panels is higher at 9 AM. compared with 3 PM., despite nearly identical solar radiation levels, as illustrated in Figure 5. This is because the ambient temperature at 9 AM is lower than that at 3 PM, and this shows that the ambient temperature has a significant effect on the performance of the solar panels.

Also, the obtained results can be compared with the results reported by Muslim and Ghadhban [26], as shown in Figure 8. The electrical performance of Muslim was reported to be better than the current study, with a higher improvement rate of 17% than an uncooled panel, while the current study showed a maximum improvement of 8%. The difference is due to the difference in operating conditions and to Muslim's ability to control the flow rate and angle of injection of the water to optimize the cooling. Consequently, it is observed that the non-uniform cooling has significant impact on the electrical efficiency of a solar panel.

In addition to the results above, in Figure 9 a comparison was made between the practical results obtained via the PV200 device for the PV panels on 26 April 2024 at 1 PM and the results obtained via MATLAB (R2012a), through a numerical analysis approach based on the algorithm previously employed by Mahmood et al. [49] for the same panels with the same specifications. This was done to verify the experimental results with greater accuracy and to further validate the findings obtained practically. The comparison was performed by collecting temperature data of each of the 36 solar cells in the panel, measured by the temperature sensor HG01, and the solar radiation levels measured at the same moment by the measuring devices used in the experimental set-up (200R). The electrical power values obtained from MATLAB simulations were 42.8 W, 37.6 W and 41.4 W for PV1, PV2 and PV3 respectively, whereas the experimental measurements yielded 43.3 W, 39.1 W, and 41.2 W as shown in Figure 9. This resulted in discrepancies of 0.5 W, 1.3 W, and 0.2 W. Additionally, voltage variations were recorded at 0.12%, 0.05%, and 0.4%, while current

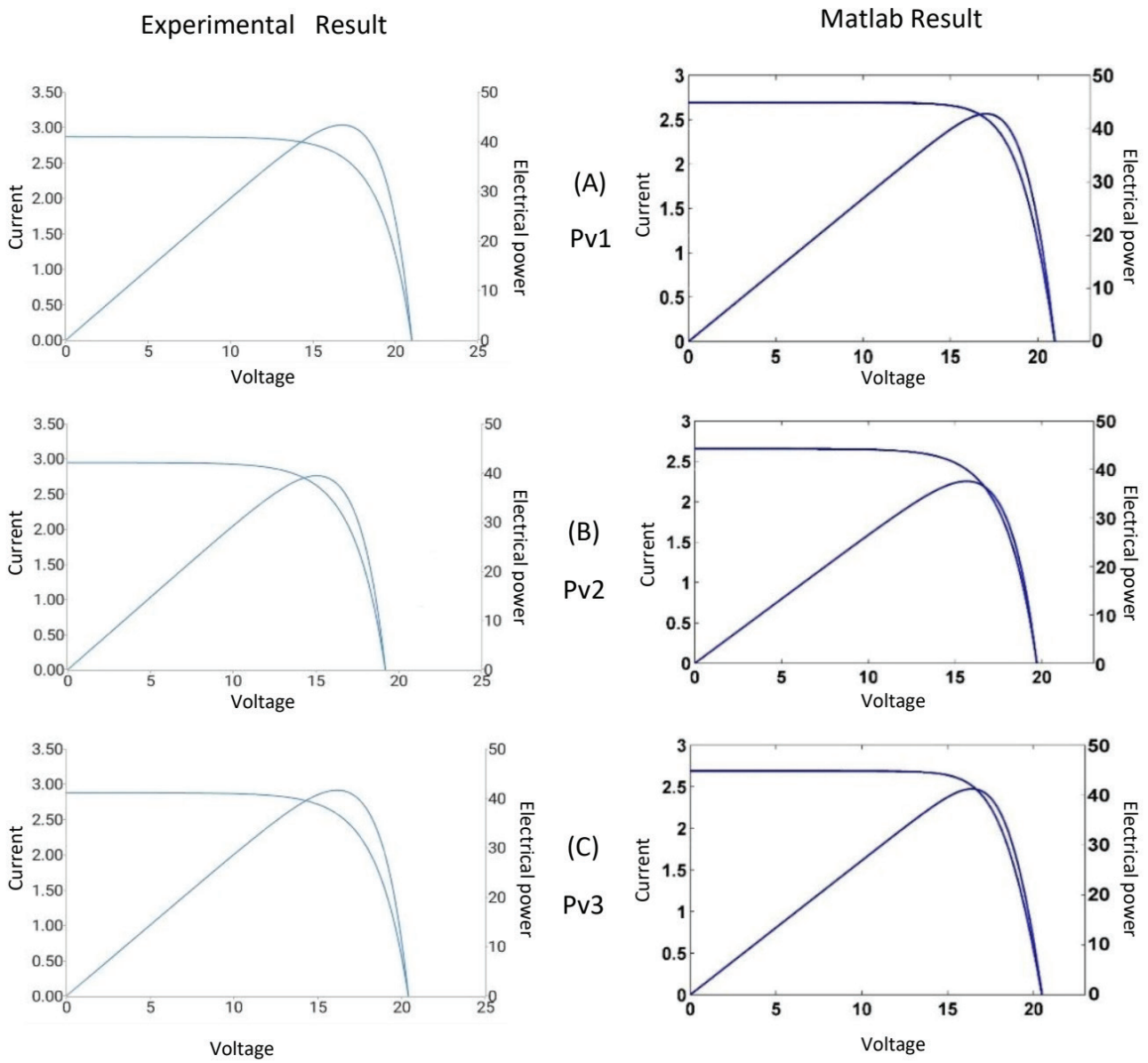

Figure 9. Comparison between MATLAB simulation results and experimental results.

variations were observed at 3%, 10%, and 7%, respectively. These results demonstrate a slight variation in the comparative findings, which can be attributed to practical operating conditions such as wind speed, dust accumulation, human error, or the accuracy of the measuring devices.

CONCLUSION

This paper presents an experimental examination conducted in Baghdad, Iraq, to examine the effect of non-uniform cooling on the performance of photovoltaic panels (type HS-1850) installed at a 25-degree angle. Three solar panels were used: two were cooled, with the first panel being uniformly cooled by placing an acrylic cooling chamber underneath the back of the panel. The second panel was non-uniformly cooled by using an acrylic water channel beneath the solar panel and inside the acrylic cooling chamber. For comparison the third panel was not cooled. The results demonstrated the impact of cooling and non-uniform cooling on the performance of the photovoltaic panels.

1. The experimental results indicate that the electrical power outputs obtained were 38.5W, 35.6W and 37.4W, with the electrical efficiencies of 13.1%, 12.09% and 12.7% for the uniformly cooled panel, the uncooled panel and the non-uniformly cooled panel, respectively.
2. The performance of the uniformly cooled panel was the greatest improvement of 8% over the traditional

uncooled panel. But the gain in efficiency was reduced by 3% for the non-uniformly cooled panel, showing how the uniformity of cooling affects the solar panel efficiency.

3. The experimental measurements were compared with the MATLAB simulation results to assess the accuracy of the model. The differences in electrical power were 0.5 W for the uniformly cooled panel, 1.4 W for the uncooled panel and 0.2 W for the non-uniformly cooled panel. The corresponding deviations in voltage were 0.12%, 0.05%, and 0.4%, while those in current reached 3%, 10%, and 7%, respectively. These discrepancies may be associated with variations in actual operating conditions, including wind speed and dust accumulation, as well as potential measurement errors and the accuracy limitations of the instruments used.
4. All these results indicate that cooling solar panels to improve their performance and that the cooling is uniform and free from any significant thermal variation is key to achieving optimal electrical performance.

Future studies may try different cooling methods to ensure uniform cooling. In addition, the study can be generalized to different environmental conditions and operational parameters such as water flow rate, water cooling and different types of cooling fluids to improve the cooling process and achieve maximum electrical performance.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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