INVESTIGATION ON PERFORMANCE OPTIMIZATION FOR SOLAR PANEL BY WATER-BASED COOLING SYSTEM

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ABSTRACT

The increasing demand for sustainable energy has accelerated the development of renewable energy technologies. Solar photovoltaic (PV) systems have become an important option. However, their performance is affected by high operating temperatures, particularly under tropical conditions. This study investigates the effectiveness of a water-based cooling system for solar panels, where high temperature is the major concern. Reduced power output and heat stress are some consequences of poor cooling effects which can affect PV performance and long-term reliability. This research has developed an experimental model for a water-based cooling system to optimize solar panel performance. The experimental evaluation considered different outdoor solar conditions, including variations in irradiance and ambient temperature. By using a 10 W solar panel with Voc of 22.1V and Isc of 0 .61A, the efficiency and output in terms of voltage, current and power are measured. The formation of a thin water film on the PV surface reduced the operating temperature, resulting in improved voltage stability, current output, and conversion efficiency. This experiment recorded an average temperature drop of 16°C and an increase in conversion efficiency of 21%. The findings demonstrate the potential of a simple and low-cost water-based cooling approach for improving PV performance under hot and humid tropical conditions.

Keywords: Cooling system, water-based, photovoltaic, solar panel, water spray, renewable energy, sustainability, thermal management

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1. INTRODUCTION

The increasing demand for electricity and the environmental impacts associated with fossil fuel-based power generation have encouraged the wider adoption of renewable energy technologies [1, 2]. Among these technologies, solar photovoltaic (PV) systems have received significant attention due to their ability to convert sunlight into electricity with low operational emissions. In line with this global transition, Malaysia has committed to achieving net-zero carbon emissions by 2050 through national initiatives such as the National Energy Transition Roadmap (NETR), which targets a renewable energy share of 40% by 2035 and 70% by 2050 [3]. Solar energy is particularly suitable for Malaysia due to its high solar irradiance throughout the year. Crystalline silicon (c-Si) PV technology remains the dominant approach for converting solar energy into electricity [4]. However, the performance of PV modules under tropical conditions, such as those experienced in Pagoh, Malaysia, is affected by high operating temperatures and dust accumulation. These factors can reduce energy conversion efficiency and accelerate performance degradation over time [5–9]. Although PV modules convert only a portion of the incoming solar radiation into electricity, a significant amount of the remaining energy is converted into heat, increasing the module operating temperature [5]. Excessive heat can induce thermal stress and contribute to long-term degradation of PV components [10]. Therefore, effective thermal management remains an important research area for improving PV performance and reliability.

This study investigates the thermal and electrical performance of a 10 W monocrystalline PV panel using a simple water-based front-surface cooling system. Water was selected as the cooling medium due to its high specific heat capacity and good heat transfer properties, which enable effective heat removal from the PV surface [11]. The proposed active water spray cooling method was evaluated against passive air cooling and a non-cooled condition to determine its effect on panel temperature, electrical output, and conversion efficiency. The study provides an experimental assessment of a low-cost water-based cooling approach suitable for PV applications under hot and humid tropical conditions [4, 5, 12].

2. LITERATURE REVIEW

This section reviews existing photovoltaic (PV) cooling technologies and discusses their advantages and limitations under different operating conditions.

2.1 Comparative Analysis and Critical Evaluation of Photovoltaic Cooling Technologies

Alternative thermal management strategies for photovoltaic (PV) modules encompass a wide spectrum of configurations, ranging from passive sensible and latent heat absorbers to active backside convective networks [7]. Among passive technologies, Phase Change Materials (PCMs) occupy a prominent role due to their ability to regulate operating temperatures without requiring parasitic electrical power. PCMs absorb sensible heat in a solid state, maintain a quasi-constant temperature by absorbing latent heat of fusion during phase transition (melting), and subsequently store additional sensible heat in a liquid state. Despite exhibiting a high latent heat of fusion per unit volume and long-term operating reliability in high-temperature environments, the integration of PCMs is constrained by substantial initial capital investments and the low intrinsic thermal conductivity of typical phase-change compounds [13]. Conversely, active air-cooling schemes utilize forced convection via mechanical fans directed at either the front or rear module faces, whereas thermoelectric cooling (TEC) modules employ Peltier junction devices driven by direct current (DC) to actively pump heat through conductive transfer mediums [14]. While air cooling remains structurally simple, its effectiveness is fundamentally limited by the low heat transfer coefficient of air. Similarly, TEC systems suffer from active parasitic power consumption that often offsets the net electrical gains of the PV module [15]. Rear-mounted active liquid cooling configurations, such as forced water circulation through heat exchangers or pipe networks, offer a significantly higher heat transfer potential. For instance, a hybrid wick heat pipe photovoltaic-thermal (PV/T) system can harvest thermal energy to achieve overall thermal, electrical, and energy efficiencies of up to 63.65%, 8.45%, and 10.26%, respectively [16]. Nonetheless, the high manufacturing, installation, and plumbing costs associated with rear-surface forced circulation networks restrict their economic feasibility for large-scale solar arrays.

Front-surface water-based cooling methodologies bypass the high conductive thermal resistance of rear panel layers by extracting heat directly through the front glass [9]. Among these approaches, liquid immersion cooling (submerging modules under a shallow fluid layer, typically at a 1 cm depth) can stabilize cell temperatures between 31°C and 39°C, improving electrical efficiency by up to 17.8% [15]. However, immersion setups are structurally incompatible with floating solar platforms, exhibit degraded performance on cloudy days, and risk electrical leakage or localized degradation from ionized water species [1,15-17]. Conversely, front-surface water spraying has gained traction as a more versatile alternative, distributing active water as a thin, convective flowing film directly over the front glass cover [17]. This technique typically outperforms backside cooling configurations, yielding electrical power gains of 14.6% to 15% and cooling the panel to a baseline of 35°C [9]. A thermodynamic comparison shows that while liquid immersion offers up to a 40°C temperature reduction and forced rear water circulation yields a 20–30°C reduction, front spraying provides a maximum drop of 20°C with an empirical average of approximately 16°C [1,17]. Crucially, front-spraying provides immediate thermal regulation while simultaneously acting as a self-cleaning mechanism to wash away dust and debris [17]. Despite these advantages, its practical viability is constrained by continuous water consumption, pump requirements, and the long-term risk of mineral scale deposition clogging the spray nozzles [17]. Despite the effectiveness reported for various PV cooling techniques, many existing approaches require complex structures, additional energy input, or high implementation costs. Therefore, simple and low-cost cooling methods remain relevant, particularly for small-scale PV systems operating under hot and humid conditions. This study focuses on a manually operated front-surface water spraying system as a practical approach for improving PV thermal management.

3. METHODOLOGY

This section presents the development of the proposed water-based PV cooling system and the experimental procedure used in this study. The prototype design, PV module specifications, spray configurations, test conditions, and measurement methods are described. The experimental evaluation was carried out to determine the effect of water spraying on PV panel temperature and electrical performance under outdoor tropical conditions.

3.1 Prototype Design and PV Module Specification

The prototype consisted of a PV panel support frame and a water spray stand, both fabricated from 1/2-inch uPVC pipes. The PV support frame had a base of 15 in × 5.5 in and a fixed tilt angle of 20°, achieved using front and rear supports with heights of 13 in and 18 in, respectively. The spray stand had a base of 17 in × 8 in × 0.5 in and included a 19 in vertical pipe connected to a horizontal pipe fitted with a detachable spray head above the PV panel for front-surface water spraying. A 10 W monocrystalline PV panel (TYL-010M) was used in the experiment, and its specifications are listed in **Table 1**.

Table 1. Specification of chosen PV panel

Name	Value
Module Type	TYL-010M
Peak Power (P_{MAX})	10W
Production Tolerance (%)	± 3
Maximum Power Current (I_{MP})	0.56A
Maximum Power Voltage (V_{MP})	18.00V
Short Circuit Current (I_{SC})	0.61A
Open Circuit Voltage (V_{OC})	22.3V
Dimension (mm)	445×190×25
Maximum System Voltage	1000V

3.2 Water Spray Configuration and Model Development

Figure 1 illustrates the development of the proposed water-based cooling system **Figure 1**(a) shows the PV panel mounted on the supporting frame, which was designed to maintain a fixed tilt angle of 20°. The structure was fabricated to provide sufficient stability during outdoor testing. **Figure 1**(b) shows the water inlet connection from the tap supply to the spray system. A valve was installed to regulate the water flow rate entering the spray tube. The continuous water supply allowed the flow rate to be adjusted according to the experimental requirements. **Figure 1**(c) shows the spray tube configurations used in this study. Three spray tubes were prepared by drilling 2 mm diameter holes with different numbers of openings: 5, 7, and 9 holes. These configurations were used to obtain different water flow rates. The water flow rate was calibrated using the volumetric Bucket Method. The flow rate was determined by dividing the known volume of water collected in a container by the measured filling time. The average values obtained were 38.6 mL/s, 53.4 mL/s, and 68.2 mL/s for the 5-hole, 7-hole, and 9-hole configurations, respectively.

(a) (b) (c)

Figure 1. Model Development (a) PV panel on top of the stand (b) Inlet connection of sprayer stand (c) Sprayer with 5, 7, and 9 holes

3.3 Experimental Site and Measurement Conditions

The experiment was conducted at the Education Hub, Pagoh, Malaysia (2°08'58.1"N, 102°44'06.4"E). Although the experimental campaign was conducted on a single day, measurements were performed during three different periods to represent different solar conditions: morning (10:00 A.M.–12:00 P.M.), afternoon (12:00 P.M.–2:00 P.M.), and evening (2:00 P.M.–5:00 P.M.). The experiment focused on evaluating the effect of water cooling on PV thermal and electrical performance. Ambient temperature and PV surface temperature were measured throughout the experiment. Other environmental parameters, including wind speed, relative humidity, and dust accumulation, were not considered in this study and are acknowledged as limitations. A single monocrystalline PV panel was used throughout the experiment. The three water flow-rate configurations (38.6, 53.4, and 68.2 mL/s) were tested sequentially while maintaining the same PV module, orientation, measurement instruments, and tilt angle to ensure consistency.

3.4 Experimental Procedure and Data Collection

Before each experimental run, the PV panel was cleaned and maintained in a dry condition. The panel was exposed to solar radiation for 5 minutes to achieve stable thermal condition before the cooling process started. The water spraying system was then activated for 1 minute to allow a uniform water film to form across the front glass surface. For each flow-rate configuration, the PV surface temperature, output voltage, output current, and power were measured three times under stable weather conditions. Measurements were recorded after the cooling system reached a steady operating condition. A recovery period was provided between consecutive tests to allow the PV panel temperature to return close to its ambient condition, reducing the influence of previous cooling cycles. Solar irradiance was continuously monitored using a Seaward Solar Survey 200R irradiance meter, which was positioned parallel to the PV module surface. Irradiance values were monitored throughout each measurement period to ensure that the tests were conducted under relatively stable solar conditions. The average values obtained from repeated measurements were used for further analysis to improve data reliability and comparison between different water flow-rate configurations.

Since the electrical measurements were conducted under outdoor operating conditions, the obtained power values were mainly used for comparative analysis between the cooled and non-cooled PV module conditions. The electrical power values were calculated from the measured voltage and current and were used as indicators to evaluate the effect of different cooling configurations. Therefore, the reported values represent the actual experimental performance of the PV module under the applied test conditions and should not be considered as the rated maximum power output under Standard Test Conditions (STC), where the module is specified at 10 W.

4. RESULT AND DISCUSSION

The experimental results are presented based on the effect of water spraying on PV temperature, electrical output, and conversion efficiency. The performance of the cooling system was evaluated under three operating periods: morning, afternoon, and evening. The reduction in operating temperature indicates the potential of water spraying to improve PV operating conditions.

4.1 Temperature Before and After Cooling

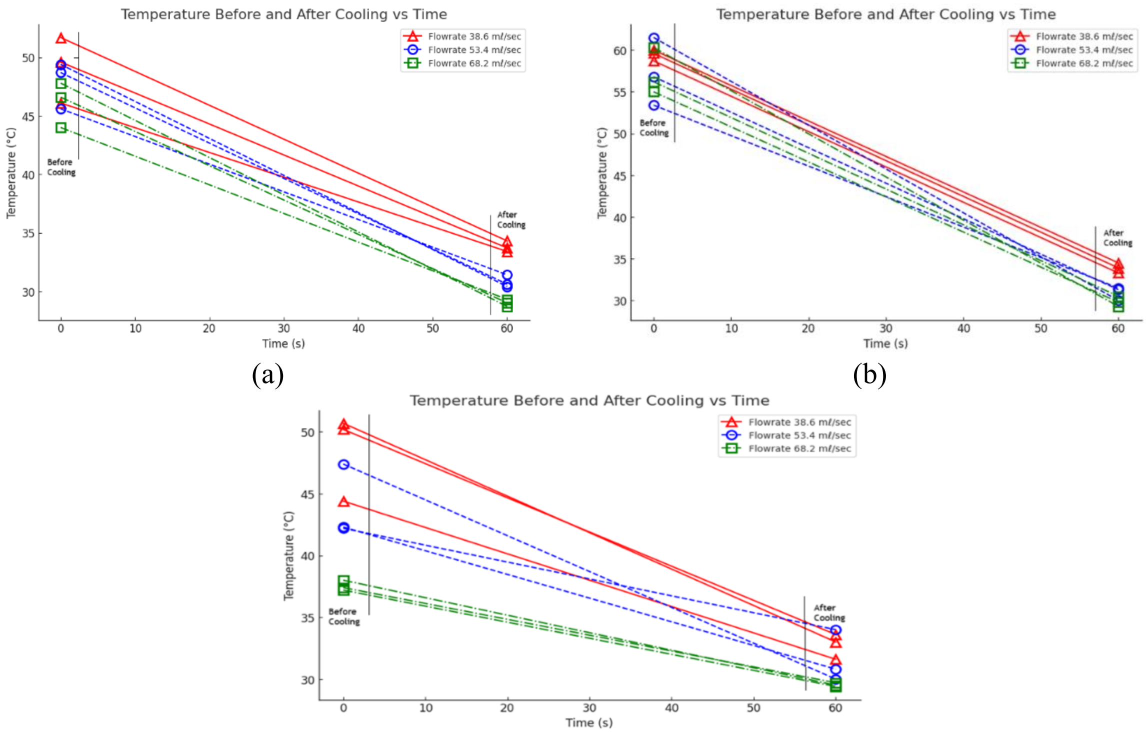
Figure 2 shows the graph of temperature before and after cooling vs time for 3 different sessions, morning, afternoon and evening. During each measurement session, three readings were recorded for every flowrate to ensure consistency and reliability of the experimental data. **Figure 2**(a) is in the morning which irradiance was observed at 737 to 1006 *W/m²* whereas for the temperature around 33°C to 36°C. Data collection began at 10 o'clock is because the irradiance before data captured was below 500W/m² due to heavy cloud conditions. The panel temperature before cooling reported ranged from 44.0°C to 51.7°C. After cooling, panel temperature varies from 28.7°C to 34.3°C. Cooling resulted in a significant reduction in *Tmod*, averaging roughly 16°C reduction.

Figure 2(b) shows that the highest panel temperatures were recorded during the afternoon because of the higher solar irradiance, resulting in greater heat accumulation within the PV module. Recorded irradiance levels range from 758 W/m² to 1011 W/m². Ambient temperature consistent, ranging from 36°C to 39°C during the data collection period. In terms of temperature, panel temperature before cooling ranges from 55.0°C to 61.5°C. Panel temperature drops significantly after cooling to a range of 29.3°C to 34.5°C. This temperature reduction is consistent with previous studies reporting that direct water cooling can effectively reduce PV operating temperature by improving heat transfer from the module surface [9]. The cooling process results in a substantial reduction in panel temperature, averaging around a 26°C drop.

Figure 2(c) illustrates the transient thermal response of the PV module under the lower solar intensities of the evening session. The recorded irradiance levels vary between 467 W/m² and 803 W/m², which are lower than the morning and afternoon readings due to the current time of day while the ambient temperature remained rather stable, fluctuating between 35°C and 37°C during the data collection time. Pre-cooling panel temperatures range from 37.2°C to 50.7°C. The panel cools to a range of 29.4°C to 34.0°C. Panel temperature drops dramatically during the cooling process, typically by 16°C.

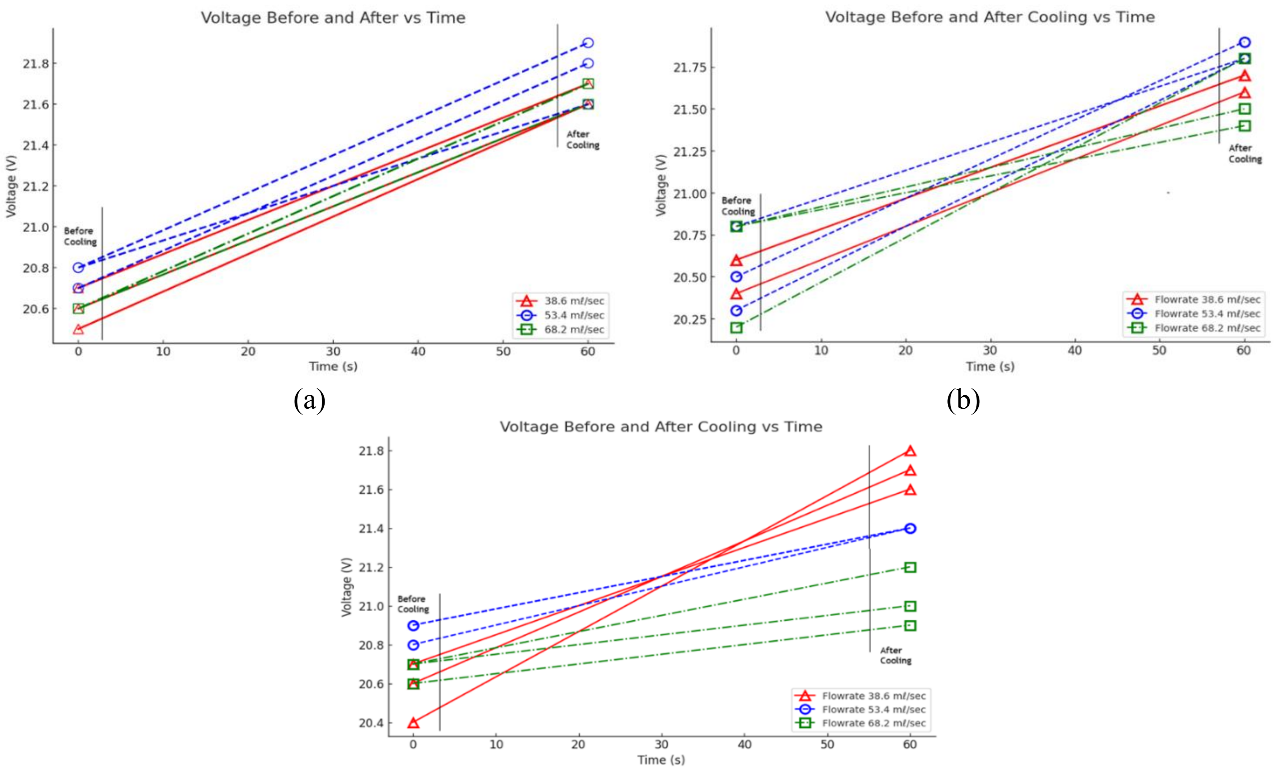
4.2 Voltage Performance

Figure 3 shows graph of voltage before and after cooling vs time. In the morning, **Figure 3**(a) shows voltage before cooling varies from 20.5*V* to 20.8*V*. Voltage after cooling varies from 21.6*V* to 21.9*V*. The increase in voltage after cooling is consistent with the negative temperature coefficient of crystalline silicon PV cells. As the operating temperature decreases, the open-circuit voltage increases, leading to improved electrical performance. During the afternoon, **Figure 3**(b) shows voltage value before cooling ranges from 20.2*V* to 20.8*V* while increases slightly, ranging from 21.4*V* to 21.9*V* after the cooling. The increase in voltage suggests an improvement in panel performance due to lower operating temperatures. In the evening, **Figure 3**(c) shows ranges for pre-cooling voltages are 20.4V to 20.9V. Voltage after cooling ranges from 20.9V to 21.8V. A small voltage increase after cooling indicates better panel performance.



(a) (b) (c)

Figure 2. Temperature before and after cooling vs Time (a) Morning, (b) Afternoon, (c) Evening



(a) (b) (c)

Figure 3. Voltage before and after cooling (a) Morning, (b) Afternoon, (c) Evening

4.3 Current Performance

During morning, current before cooling varies from 0.42A to 0.65A. Current after cooling varies from 0.51A to 0.65A.

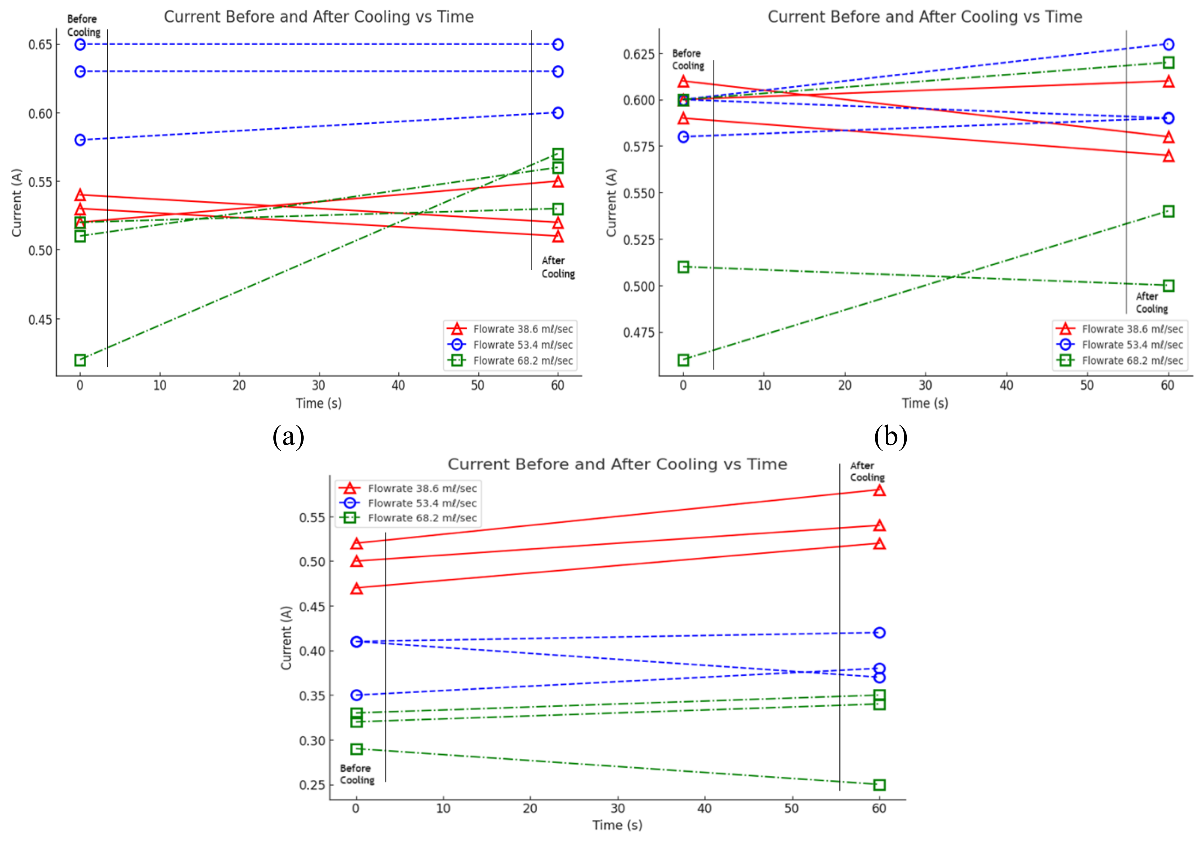


Figure 4. Current before and after cooling (a) Morning, (b) Afternoon, (c) Evening

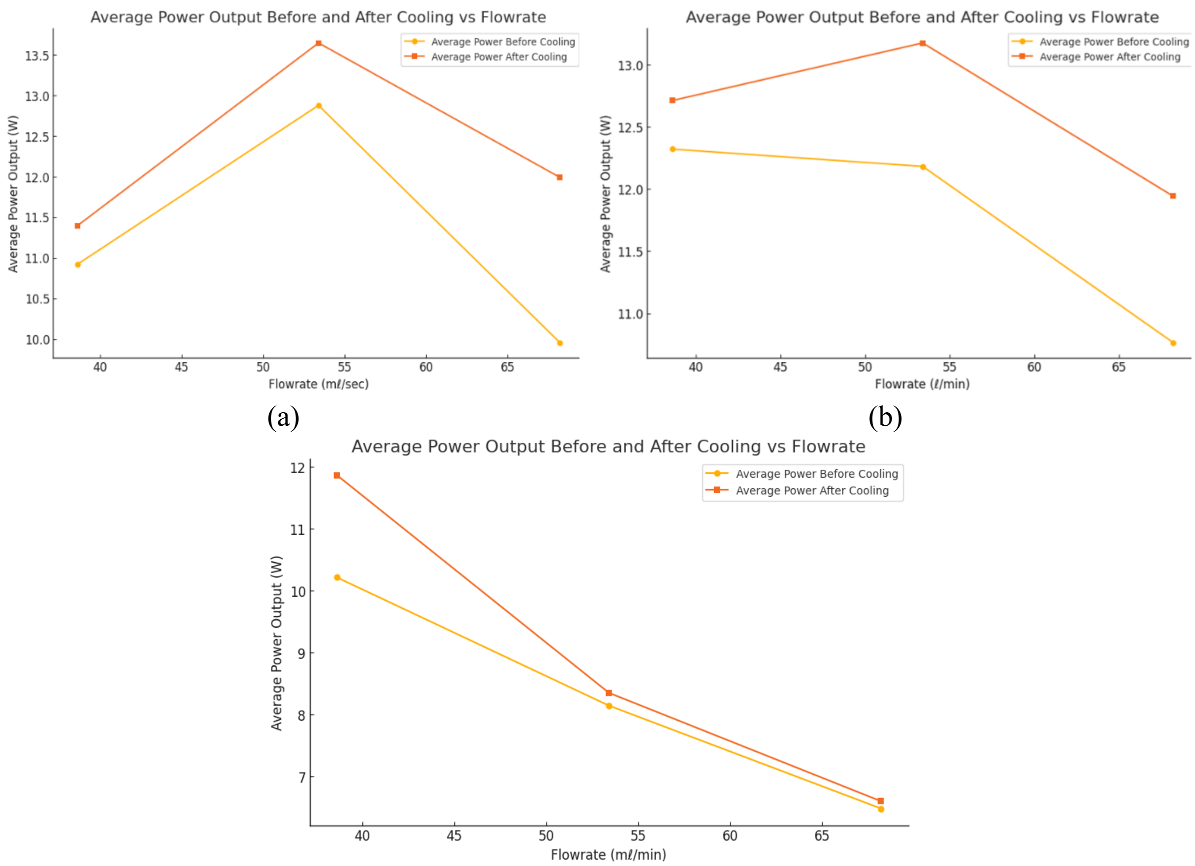
In the afternoon, there is a slight increase in current after cooling, contributing to the overall improvement in power output. Before cooling, current values range from 0.46A to 0.61A, while after cooling ranges from 0.50A to 0.63A. Before cooling, current values ranged from 0.29 to 0.52 amps. The current after cooling ranges from 0.25 to 0.58A. Compared with voltage, the change in current after cooling was relatively small. This behaviour is expected because PV current is primarily influenced by solar irradiance, whereas temperature has a greater effect on voltage. Nevertheless, slight improvements in current were observed, indicating more stable electrical operation after cooling. The result is illustrated in **Figure 4**.

4.4 Average power output

Figure 5 shows the average power output before and after cooling. In the morning, **Figure 5**(a) shows an increase of power output after cooling for all flowrates.

This indicates that cooling generally improves the performance of the system, resulting in higher power output. The 53.4 mℓ/sec flow rate has the highest average power output both before and after cooling, suggesting it might be the optimal flow rate for this system in terms of power output efficiency. The 68.2 mℓ/sec flow rate shows the largest increase in power output after cooling, indicating that higher flow rates can significantly improve performance, but starting power output was lower due to irradiance.

In the afternoon, **Figure 5**(b) shows the average power output before cooling are 12.320W, 12.181W, and 10.765W for each flowrate 38.6, 53.4 and 68.2 mℓ/sec respectively while for power after the cooling are 12.710W, 13.174W and 11.942W. Cooling significantly reduces the panel temperature, resulting in an average reduction of approximately 26°C, which positively impacts the panel's performance. The average power output increases for all flow rates after cooling, with the flow rate of 53.4 mℓ/sec showing the most substantial improvement.



(a) (b)

(c)

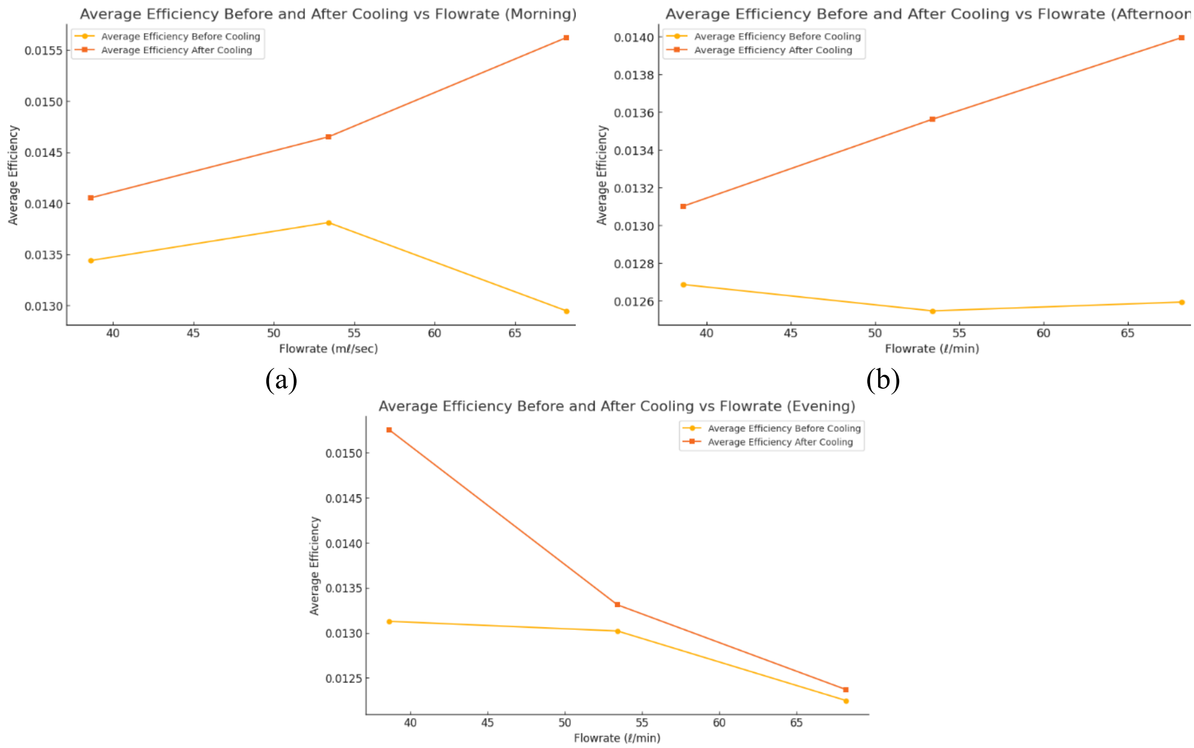
Figure 5. Average Power Output before and after cooling for each flowrate (a) Morning, (b) Afternoon, (c) Evening

In the evening, **Figure 5**(c) shows the average power output before cooling are 10.212W, 8.139W, and 6.476W for each flowrate 38.6, 53.4 and 68.2 mℓ/sec respectively while for power after the cooling are 11.865W, 8.346W and 6.594W. The maximum power increase can be observed at the 38.6 *mℓ/sec* with 1.652W difference while 0.207W and 0.118W power increase by flowrate of 53.5 and 68.2 mℓ/sec respectively. This is because towards the evening, the irradiance is getting lower, which clearly as depicted in **Figure 5**.

The optimum flow rate varied throughout the day because the thermal load imposed on the PV module changed with solar irradiance. During periods of higher irradiance, larger water flow rates removed heat more effectively. Under lower irradiance conditions in the evening, additional cooling produced only marginal improvements because the panel temperature was already relatively low.

4.5 Data Efficiency

Figure 6 shows the average efficiency of before and after cooling for all different periods**.** The highest efficiency improvement (21.83%) was obtained at 68.2 mL/s during the morning. Under this operating condition, the higher flow rate provided more effective heat removal, reducing thermal losses within the PV module. In contrast, flow rates of 38.6 mℓ/sec and 53.4 mℓ/sec exhibited lower efficiency increases of 4.43% and 6.01%, respectively.



(c)

Figure 6. Average Efficiency before and after cooling for each flowrate (a) Morning, (b) Afternoon, (c) Evening

During the afternoon, efficiency improvements were observed for all three flow-rate configurations. The highest increase was recorded at a flow rate of 68.2 mL/s, with an efficiency improvement of 11.24%, followed by 53.4 mL/s with 8.13%, and 38.6 mL/s with 3.19%. Although the highest flow rate produced the greatest improvement, the differences among the three configurations were smaller than those observed during the morning. This suggests that all flow rates were effective in reducing thermal losses under afternoon conditions, with higher flow rates providing a greater cooling effect as the PV module experienced higher thermal loading.

During the evening session, the highest efficiency improvement was obtained at the lowest flow rate of 38.6 mL/s, with an increase of 16.14%. In comparison, the efficiency improvements at flow rates of 53.4 mL/s and 68.2 mL/s were only 2.99% and 1.29%, respectively. This behaviour differs from the morning and afternoon results, as the lower solar irradiance in the evening reduced the heat generated within the PV module. Therefore, a lower water flow rate was sufficient to dissipate the remaining heat, while further increasing the flow rate resulted in only a small improvement in cooling performance. These findings suggest that the optimum flow rate for the water-based cooling system is influenced by the solar irradiance level. Higher flow rates are more effective during periods of high irradiance due to the greater thermal load, whereas lower flow rates can provide adequate cooling under reduced irradiance conditions.

5. CONCLUSION AND RECOMMENDATIONS

The experimental results showed that the front-surface water spraying system successfully reduced PV module temperature and improve electrical performance under tropical outdoor conditions. The cooling performance varied with solar irradiance and water flow rate, indicating that the required cooling intensity depends on the thermal condition of the PV module. The largest temperature reduction was obtained during the afternoon session when the module experienced higher thermal loading, while the highest efficiency improvement was recorded during the morning session at the highest water flow rate.

A maximum temperature reduction of 26°C and an efficiency improvement of 21.83% were achieved using the proposed cooling method. These results indicate that water spraying can effectively reduce the impact of high operating temperature on PV performance, particularly in tropical climates. Compared with other cooling techniques discussed in Section 2.1, the proposed system provides a simpler approach with lower system complexity, making it suitable for small-scale PV applications. However, the requirement for a continuous water supply and manual adjustment of the flow rate should be considered in future improvements to enhance system reliability and practical deployment.

Nevertheless, this study was limited to short-term outdoor measurements under the tested environmental conditions. The use of a continuous water supply and manual flow adjustment may affect the practicality of the system for long-term operation. Future work should focus on evaluating the system over extended periods, including different weather conditions, water usage and sustainability considerations, as well as implementing an automated flow control method based on the PV operating temperature.

6. AI USAGE DECLARATION

The authors declare that the scientific work was carried out entirely by the authors. This includes the experimental design, data collection, calculations, data analysis, interpretation of the results, figures, tables, references, and conclusions. AI was not used to generate research findings, analyse the data, perform calculations, or make scientific conclusions. However, ChatGPT (OpenAI) was used only to improve the language and readability of the revised manuscript. It was used to help correct grammar, improve sentence structure, make the writing clearer, and enhance the overall flow of the manuscript. All AI-generated text was carefully reviewed, edited, and verified by the authors to ensure accuracy, academic integrity and originality.

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