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Optimization of Photovoltaic Performance Using a Water Spray Cooling System with Different Nozzle Types

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ABSTRACT

Applying solar radiation as a renewable energy source using photovoltaic panels has problems, such as work efficiency decreasing when the photovoltaic cell temperature is above the working temperature, thus requiring a cooling method. This research examines the cooling effect of photovoltaic panels using water spray with various types and diameters to reduce the temperature and performance of photovoltaic panels, which was carried out experimentally with solar radiation at 08:00-15:00 local time. The research results show that the water spray cooling system can reduce the temperature of the photovoltaic panel from 61.96 to 36.51℃ and increase efficiency from 10.98 to 14.47% with variations in the full cone nozzle with a hole diameter of 2 mm. Full cone nozzles can provide the best cooling performance compared to hollow cone nozzles and flat fan nozzles due to the more even distribution of water spray on the surface of the photovoltaic panel. Using different nozzle diameters also influences cooling. Based on the research results, the water spray cooling system effectively increases the work efficiency of photovoltaic panels with a 2 mm total cone nozzle variation, producing the highest efficiency.

1. INTRODUCTION

The sun can produce electrical and thermal energy through radiation [1]. This solar radiation can be utilized either directly or indirectly. In various places worldwide, concerted efforts are underway to harness solar energy to reduce reliance on fossil fuels for electricity generation [2]. Countries with high solar radiation potential have additional advantages in utilizing solar energy sources as a source of electrical energy. Solar energy as a source of electrical energy can be utilized through photovoltaic (PV) solar cells [3].

Various photovoltaic (PV) solar cells can convert solar radiation into electrical energy, including monocrystalline, polycrystalline, and thin-film technologies [4, 5]. Typically, PV solar cells exhibit an electrical conversion efficiency rate ranging from 9% to 12%, with over 80% of the incident solar energy being absorbed as heat. This absorbed heat can increase the temperature of the PV solar cells [6]. The ideal working temperature of PV solar cells is 25℃, but under natural conditions, the ambient temperature may vary and exceed the ideal working temperature [7-9]. Increasing temperature above the ideal temperature can decrease the output power and working efficiency of PV solar cells [10-12]. This decrease is a significant challenge in using photovoltaic panels, so a cooling system is needed to reduce and control the temperature of solar cells.

Several researchers have tried to seek solutions for reducing and regulating the temperature of solar PV cells to achieve peak power output and efficiency [13-15]. In general, cooling methods for photovoltaic panels can be classified as active and passive cooling [14, 16, 17]. Passive cooling, such as using PCM material and adding a heatsink, does not require additional energy sources in the cooling process but has poor cooling performance compared to active cooling. Research conducted by Arifin et al. [18], cooling photovoltaic panels using PCM material reduced the temperature by 8.2℃, and research by Razali et al. [19] photovoltaic cooling using heatsinks reduces temperature by 12℃. One active cooling that can be used on photovoltaic panels is the water spray cooling system [20-22]. The water spray cooling system was chosen because it has good cooling performance, no thermal contact resistance, and is easy to apply [23]. Another benefit of the water spray system is its capability to cleanse PV panels of dust, which often accumulates due to installing PV panels in outdoor environments [24]. In this context, dust within PV panels can also reduce the performance of the PV panels [25-27].

Based on research that has been done, the water spray cooling system has proven effective in lowering the temperature of photovoltaic panels and can increase efficiency. Chen et al. [28] showed that cooling photovoltaic panels using water spray can increase work efficiency by 25%. Bevilacqua et al. [29] found that cooling photovoltaic panels using water spray can reduce temperature by 28.2% and increase efficiency by 7.8%. Research by Zhao et al. [30], cooling with water spray can reduce temperature by 10℃ and increase power output by 7.3%. Research on cooling photovoltaic panels with water spray by Javidan and

Moghadam [31] can reduce the temperature from 63.95℃ to 33.95℃ and increase power output by 47.67%. Research on cooling photovoltaic panels using water spray by Laseinde and Ramere [32] showed that it can increase efficiency by 16.65%. Hadipour et al. [33] found that adding a water spray cooling system to photovoltaic panels can increase efficiency by 33.3% and reduce the temperature from 63.95℃ to 33.68℃. Yang et al. [34] by adding a water spray cooling system to photovoltaic panels can increase efficiency by 14.3% and reduce temperature from 45℃ to 35℃.

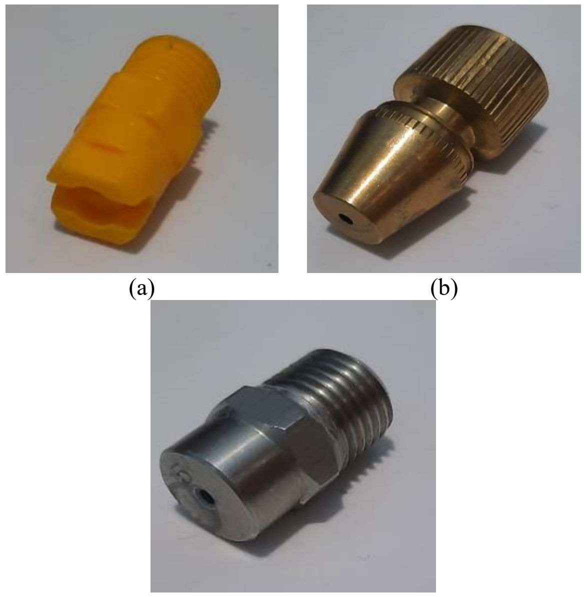
The water spray cooling system has many parameters that must be adjusted, including selection of nozzle type specifications, number of nozzles, water speed, water pressure, spraying time, and nozzle placement position [35, 36]. The choice of nozzles in the water spray cooling system is a crucial factor influencing the cooling performance outcomes. [37]. The choice of nozzle specifications plays a role in defining the water spray distribution, its characteristics, and the width of the water spray angle. Meanwhile, the water spray distribution significantly affects and determines the cooling performance of the water spray cooling system [38]. Considering these challenges, it is essential to carefully select appropriate nozzle specifications when designing a spray cooling method. Each type of nozzle exhibits a unique spray profile shape. The selection of the nozzle diameter is also important because it influences the magnitude of the spray angle and the water droplet size in each type of nozzle, thus affecting the size of the area that can be covered. The selection of the right type and diameter of the nozzle impacts even cooling on all sides of the photovoltaic panel. Evenly cooled on each side of the panel will reduce the hot spot area to maximize cooling performance. Optimal cooling performance by water spray can also optimize power output and efficiency on photovoltaic panels.

Given the challenges, employing water spray as a cooling method for photovoltaic panels holds promise and warrants further exploration and investigation. Further research is needed regarding the influence of nozzle hole geometry on water spray cooling systems to improve photovoltaic performance. This research aims to determine the effect of cooling photovoltaic panels using water spray on temperature, power output, and work efficiency of photovoltaic panels. This research also aims to determine the effect of using different types and diameters of nozzles in water spray cooling systems on cooling performance, power output, and work efficiency of photovoltaic panels. So, we can find the most optimal combination of nozzle type and diameter for cooling photovoltaic panels.

2. METHOD

2.1 Investigation of experimental settings

This study uses different nozzle types and diameters to determine the most optimal combination of cooling performance to improve photovoltaic panel performance. The types of nozzles used are full cone nozzle, hollow cone nozzle, and flat fan nozzle. The flat fan nozzle is made of ABS plastic, with a spray angle 65° and a 6.35 mm-inch thread connection. The SS304 type full cone nozzle used has a spray angle of 40° – 120° and a 6.35 mm thread connection with a size of 23×15 mm. The hollow cone nozzle is made of brass with a 6.35 mm thread connection. The nozzle hole diameters used in this study were 2 mm and 3 mm. Figure 1 shows the nozzle used in water spray research on cooling photovoltaic panels. The study was conducted experimentally using direct solar radiation from 08:00 – 17:00 in July 2023, with the test location on the rooftop of UNS Inn (Sebelas Maret University), Surakarta city, Central Java Province, Indonesia—the water spray cooling system sprays on the top surface of the PV panels. The photovoltaic panels were tilted by 12°, facing north, based on the optimal angle of the Global Solar Atlas at the test site in Surakarta.



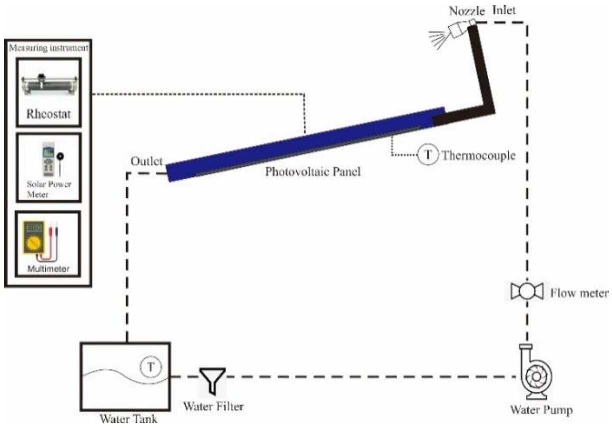
(a) (b) (c)

Figure 1. Nozzle used in research (a) Flat fan nozzle, (b) Hollow cone nozzle, (c) Full cone nozzle

In this research, the water spray cooling system was active for 1 minute in one spray. Spraying is carried out once every hour from 08:00 – 17:00 local time. The water flow is the same in all variations, namely 1.5 Lpm using a 12 Volt DC pump. The collected data from the experiments include temperature measurements, power output, solar intensity, and water discharge. Temperature and power output data collection from the PV panel is carried out after the water spray cooling system has finished spraying. The temperature data is collected using a thermocouple sensor placed at the panel's base, resulting in 9 data points. The temperature measurement results are the average of the 9-point thermocouple data collection. Solar radiation intensity measurements are done hourly at 08:00 - 17:00 local time. Solar radiation intensity was assessed with the Lutron SPM-1116SD Solar Power Meter, consistently positioned at the top of the photovoltaic panel for all variations. The power output was measured using the Heles UX838-TR multimeter with rheostat, and water discharge was measured using a flow meter. Specification data and accuracy of measuring instruments are shown in Table 1. The photovoltaic panel utilized in this research is a 50 Wp (Watt peak) polycrystalline panel manufactured by Sunwatt Aust. Pty. Ltd., with specifications detailed in Table 2.

The framework designed in this study is shown in Figure 2 below. The frame is designed with a photovoltaic panel tilt angle of 12° facing north. The framework has dimensions of 700×600×1000 mm. Installation of a photovoltaic panel, water spray cooling system, and sensors at predetermined places and locations, as shown in Figure 3.

Figure 2. Design of the test equipment framework



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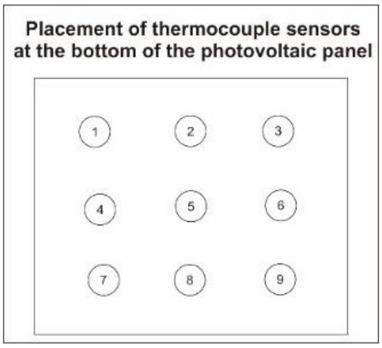


(b)

Figure 3. (a) Research design of photovoltaic panels with water spray cooling, (b) Placement of thermocouple sensors at the bottom of the photovoltaic panel

Table 1. Specification data and accuracy of measuring instruments

Measuring Instruments	Characteristics	Accuracy
K-type thermocouple	Measure PV panel temperature and water temperature with a measurement range –270 to 1260°C	± 0.4%
Tasi TA612	Thermocouple reader	± 0.2%
Lutron SPM-1116SD solar power meter	Measuring the intensity of solar radiation with a range of 0 – 2000 W/m^2	± 5%
Heles UX838-TR multimeter	Measuring the power output results of PV panels	±3% for DC current and ±0.5% for DC voltage
Flow meter	Measure water discharge with a measurement range of 1 - 5 Lpm	± 5%

Table 2. Photovoltaic panel specification

Specification	Information
Solar cell type	Polycrystalline Silicon
Open-Circuit Voltage (Voc)	21.24V
Short-Circuit Current (Isc)	3.11 A
Maximum Power (Pmpp)	50 Wp
Current at Pmax (Impp)	2.77 A
Voltage at Pmax (Vmpp)	18.0 V
Efficiency	17.6%
Dimension	670 mm×530 mm×30 mm

2.2 Work analysis parameters

Data analysis in this research was carried out by comparing the temperature and performance of photovoltaic panels without cooling, using water spray cooling with nozzle type and diameter variations. Among the performance parameters of photovoltaic panels are short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), fill factor (FF), maximum power (P_{MPP}), and efficiency (η).

The open circuit voltage (V_{OC}) represents the maximum achievable voltage capacity when no current flows within the circuit. Short circuit current (I_{SC}) is the maximum electricity when there is no resistance in the circuit. The connection between current (I) and output voltage (V) in PV panels can be described by the subsequent equation:

$$I = I_{SC}\left(1 - e^{\frac{V-V_{OC}}{m.V_T}}\right) \quad (1)$$

In this equation, it is evident that Isc represents the short-circuit current in amperes (A), V denotes the photovoltaic panel's output voltage in volts (V), and Voc stands for the open-circuit voltage in volts (V), V_T is a thermal voltage (V), and m is the diode ideality factor. The calculation of the maximum power point (P_{MPP}) produced by photovoltaic panels is formulated by the equation [39]:

$$P_{MPP} = V_{MPP} \times I_{MPP} \quad (2)$$

$$I_{MPP} = \frac{G}{G^r} \times I_{MPP}^r \quad (3)$$

$$V_{MPP} = m.V_T.\ln\left(\frac{I_{SC}-I_{MPP}}{I_0}\right) \quad (4)$$

where it is known that G represents solar radiation at the location (W/m^2), G^r is solar radiation at standard test condition (STC) (W/m^2), I^r_{MPP} is the maximum current at STC (A), m is the diode ideality factor, V_T is thermal voltage (V), Isc is short circuit current (A), I_{MPP} represents the maximum current (A), and I_0 represents the saturation current (mA). Fill factor (FF) is the division of maximum power (P_{MPP}) at V_{OC} and I_{SC}, and the working efficiency of photovoltaic panels is a comparison between the maximum power (P_{MPP}) with the solar radiation power received by photovoltaic panels (P_{light}). The equation used to find the fill factor (FF) and Efficiency (η) is shown below [40, 41]:

$$FF = \frac{P_{MPP}}{I_{SC} \times V_{OC}} = \frac{I_{MPP} \times V_{MPP}}{I_{SC} \times V_{OC}} \quad (5)$$

$$\eta = \frac{P_{MPP}}{I_{light}} = \frac{P_{MPP}}{I_{rad} \times A} = \frac{I_{SC} \times V_{OC} \times FF}{I_{rad} \times A} \quad (6)$$

3. RESULT AND DISCUSSION

3.1 Intensity of solar radiation over local time

Research on cooling photovoltaic panels with a water spray cooling system was carried out experimentally using direct solar radiation at 08:00 – 17:00 local time with the test location on the rooftop of UNS Inn (Sebelas Maret University) Surakarta city. The photovoltaic panels are tilted by 12° facing north based on the optimal angle of the Global Solar Atlas at the test location in Surakarta in July 2023. The graph of solar radiation gain throughout the day is shown in Figure 4. The most incredible intensity of solar radiation can be obtained is 1000 W/m^2 at 11:00 AM, and the lowest is 155 W/m^2 at 17:00 WIB.

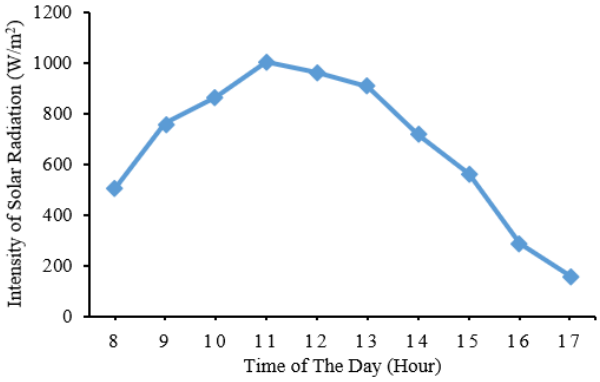


Figure 4. Local time solar radiation intensity

3.2 Effect of adding a water spray cooling system on the temperature and performance of photovoltaic panels

Photovoltaic (PV) panels have a drawback: a reduction in operational efficiency when the panel's temperature exceeds the ideal operating temperature of 25°C [7]. Weather conditions, temperature variations, and the manufacturing process of the photovoltaic panels impact their performance. This is caused by the properties of the semiconductor material contained in the photovoltaic panel cells. In cells, thermal activity increases with temperature, increasing particle movement. Consequently, the cell's internal resistance may increase due to this increased movement. As a result, this will reduce the cell's ability to convert sunlight energy into electrical current. Gap voltage, which is the potential difference between a photovoltaic cell's positive and negative layers, can decrease as temperature increases. If this gap voltage decreases due to high temperatures, the cell's ability to generate voltage and electric current will also decrease. As a result, as the panel temperature increases, their energy conversion efficiency decreases. In other words, when the temperature is high, the efficiency of converting solar energy into electrical energy tends to decrease, which means that photovoltaic panels cannot function properly to produce electrical energy [42].

Elevated operating temperatures in photovoltaic panels can influence various panel characteristics, including a decrease in the open-circuit voltage (*Voc*), consequently reducing the output power (P_{MPP}) [43]. The increase in temperature can be overcome by adding a water spray cooling system as a temperature control for photovoltaic panels. Cooling with water spray is a technique where the pressurized liquid is forced through a small hole (nozzle) to become tiny droplets. Then, the spray of these droplets is directed toward the surface of the photovoltaic panel.

Table 3. Temperature and performance of the photovoltaic panel at 11:00 AM with a solar radiation intensity of 1000 W/m^2

Variation	*Temp* (°C)	I_{MPP} (A)	V_{MPP} (Volt)	P_{MPP} (Watt)	Efficiency (%)
Without cooling	61.96	2.11	17.50	36.92	10.98
Flat fan nozzle 2 mm	41.42	2.45	18.10	44.34	13.05
Flat fan nozzle 3 mm	42.07	2.43	17.90	43.49	12.81
Hollow cone nozzle 2 mm	37.78	2.55	18.40	46.92	13.95
Hollow cone nozzle 3 mm	38.84	2.51	18.30	45.93	13.66
Full cone nozzle 2 mm	36.27	2.63	18.50	48.65	14.47
Full cone nozzle 3 mm	37.07	2.60	18.40	47.84	14.23

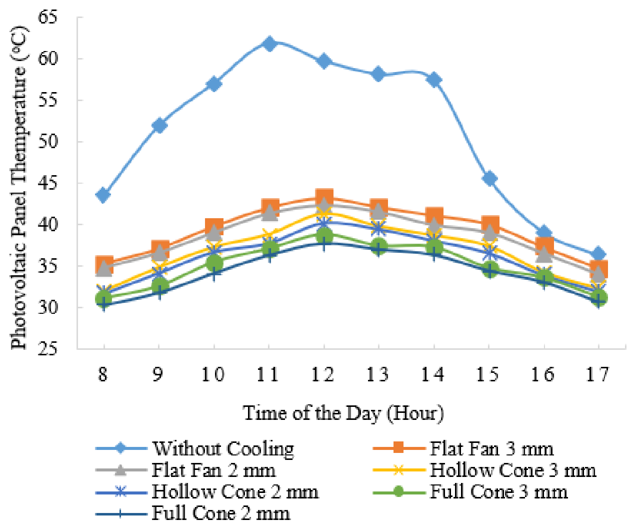


Figure 5. Photovoltaic panel temperature against time throughout the day

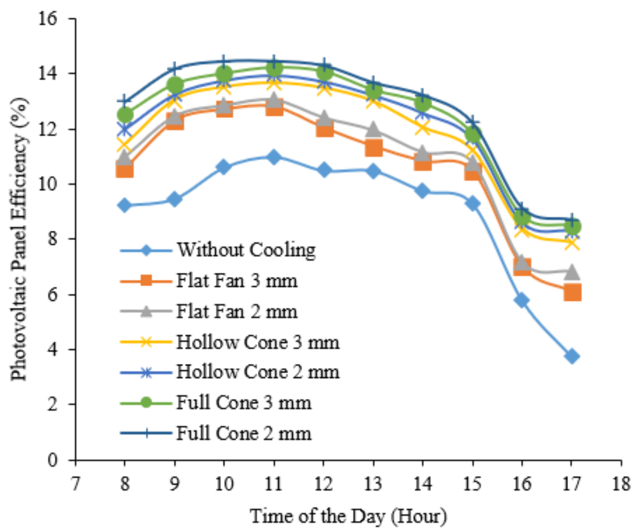


Figure 6. Photovoltaic panel efficiency against time throughout the day

Table 3 shows the performance of photovoltaic panels at 11:00 AM with a solar radiation intensity of 1000 W/m^2. The graph in Figure 5 illustrates that the temperature of an uncooled photovoltaic panel is consistently higher than when using a water spray cooler at any time of the day. There is an increase in the temperature of the photovoltaic panel when the intensity of solar radiation increases. The temperature drops results vary depending on the variation in nozzle hole geometry used. The application of a water spray cooling system on the photovoltaic panel can reduce the temperature from 61.96℃ to 36.51℃ when employing a full cone nozzle with a 2 mm diameter hole at 11:00 AM under a solar radiation intensity of 1000 W/m².

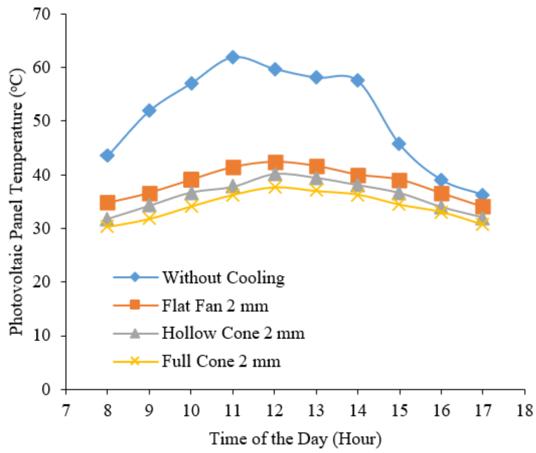
The temperature decrease in photovoltaic panels increases power output and work efficiency. Figure 6 shows a graph of the efficiency of photovoltaic panels without the addition of water spray cooling and the addition of water spray cooling over time throughout the day with each variation. The working efficiency of photovoltaic panels equipped with a water spray cooling system consistently surpasses those without cooling. Specifically, the efficiency of the photovoltaic panel at 11:00 AM under a solar radiation intensity of 1000 W/m^2 improves from 10.98% to 14.47% when a cooling system with a full cone nozzle having a 2 mm diameter is incorporated.

3.3 The effect of using different types of nozzles in water spray cooling systems on the performance of photovoltaic panels

The use of different nozzle types can provide different cooling performance. The nozzle is a component that plays a huge role in daily life. Its primary function is to control the direction and characteristics of the fluid flow. Usually, a nozzle increases fluid flow speed according to the pressure applied. The nozzle component in the water spray cooling method is an integral part of producing the shape of the water droplets and its effect on the cooling performance with water spray. An essential factor is a cooling system that can produce a uniform temperature distribution in photovoltaic panels. Selecting the right nozzle type to obtain uniform cooling using a water spray system in photovoltaic panels is necessary.

In this study, a full cone nozzle can provide better cooling than hollow cone nozzles and flat fan nozzles. A full cone nozzle has a complete circular burst profile, while a hollow cone nozzle only focuses on the outside or is hollow on the inside, so the spray does not fill the entire area. On the other hand, the flat nozzle has a burst profile shape that tends to be flat or oval, and the area affected by the burst is only the top of the photovoltaic panel, which then water flows down the panel. A full cone nozzle can provide a more even distribution of water jets on most surfaces of photovoltaic panels. It can lower panel temperatures better than flat fan and hollow cone nozzles.

Figure 7 displays a graph illustrating the average temperature of the photovoltaic panel for the day for each nozzle type. Specifically, at 11:00 AM, under a solar radiation intensity of 1000 W/m^2, a full cone nozzle with a 2 mm diameter hole can effectively reduce the photovoltaic panel's temperature from 61.96℃ to 36.27℃. In contrast, utilizing a hollow cone nozzle and a flat fan nozzle with the same 2 mm diameter at the same hour resulted in temperatures of 37.78℃ and 41.42℃, respectively. The temperature test results of photovoltaic panels with full cone nozzle, hollow cone nozzle, and flat fan nozzle with a diameter of 3 mm at 11:00 AM under solar radiation intensity of 1000 W/m^2 were 37.07℃, 38.84℃, 42.07℃. Based on research results, full cone nozzles can reduce the temperature of photovoltaic panels better than hollow cone nozzles and flat fan nozzles. The whole cone nozzle delivers a more uniform spray across the surface of the photovoltaic panel, resulting in more effective panel cooling, as demonstrated by the temperature distribution contour image of the photovoltaic panel in Figure 8 below. Better cooling performance can produce high power output and photovoltaic panel efficiency.



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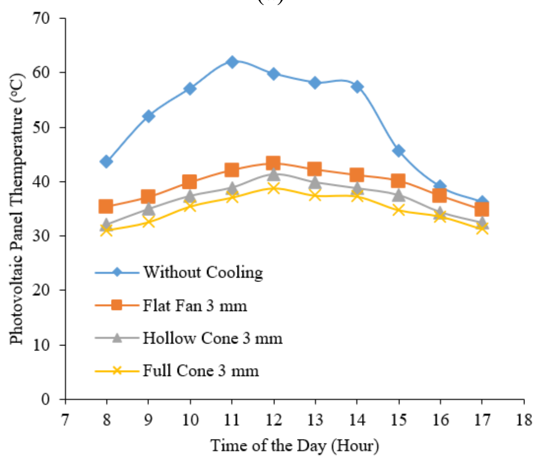
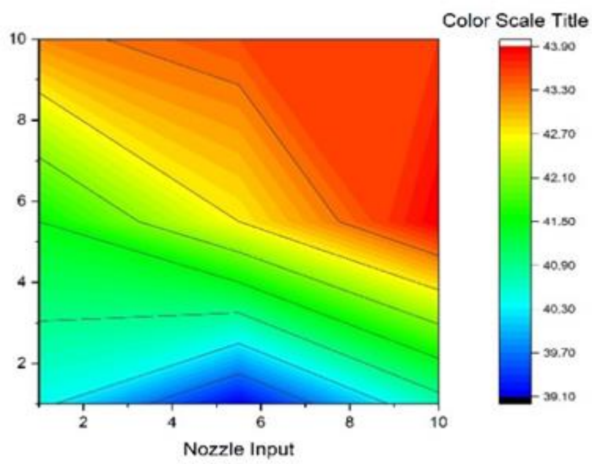


(b)

Figure 7. Photovoltaic panel temperature against time throughout the day, (a) Nozzle diameter 2 mm, (b) Nozzle diameter 3 mm



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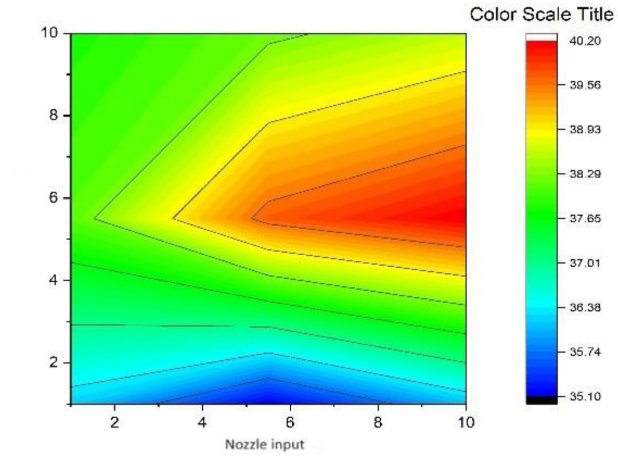

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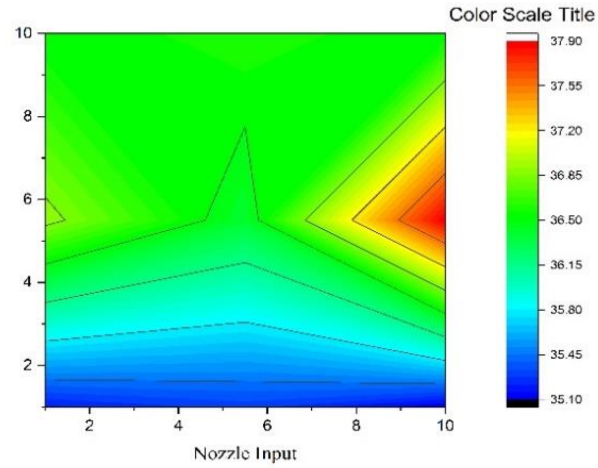
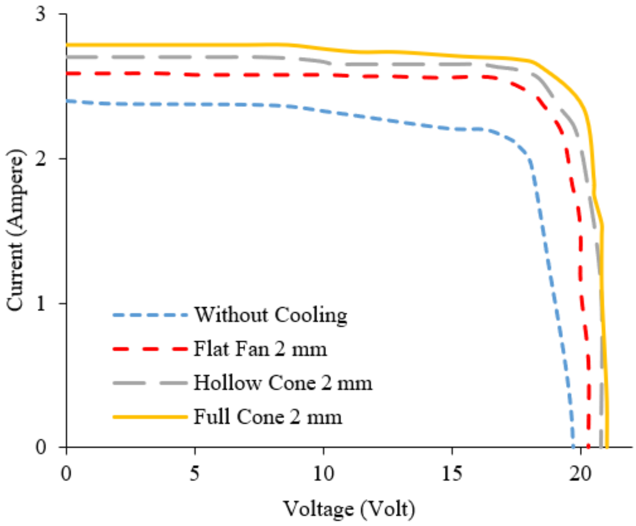


(c)

Figure 8. Temperature distribution contours on photovoltaic panels with (a) Flat fan nozzle, (b) Hollow cone nozzle, (c) Full cone nozzle



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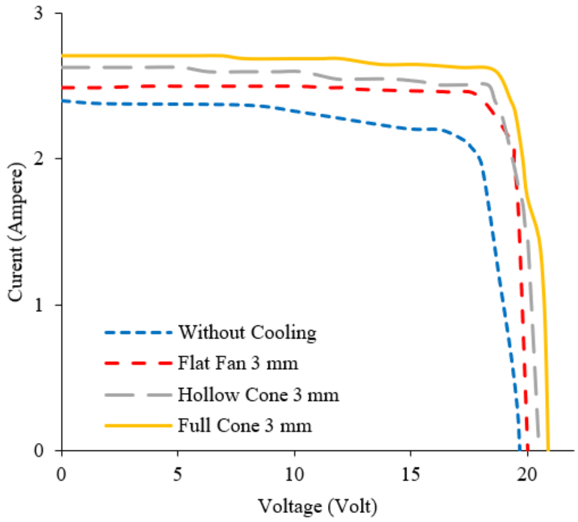
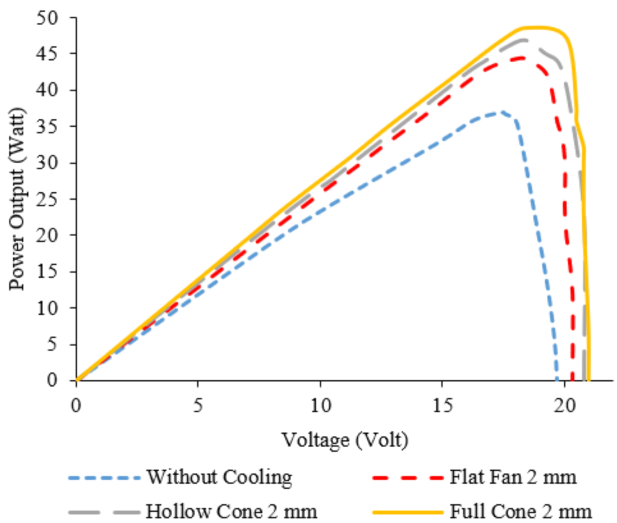


(b)

Figure 9. (a) I-V graph of a photovoltaic panel with a nozzle hole diameter of 2 mm, (b) I-V graph of a photovoltaic panel with a nozzle hole diameter of 3 mm



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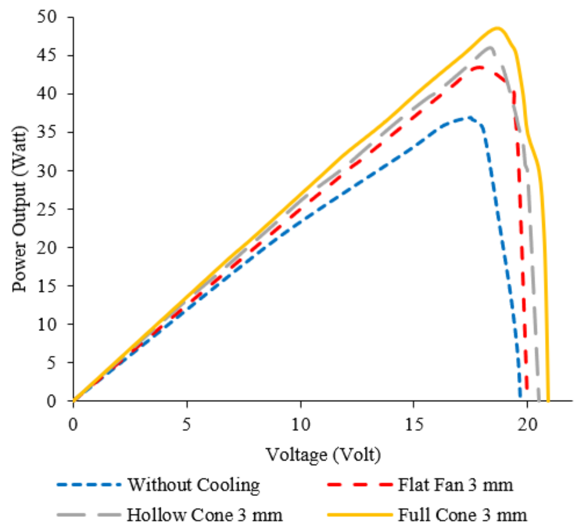

(b)

Figure 10. (a) Photovoltaic panel P-V graph with 2 mm nozzle hole diameter, (b) Photovoltaic panel P-V graph with 3 mm nozzle hole diameter

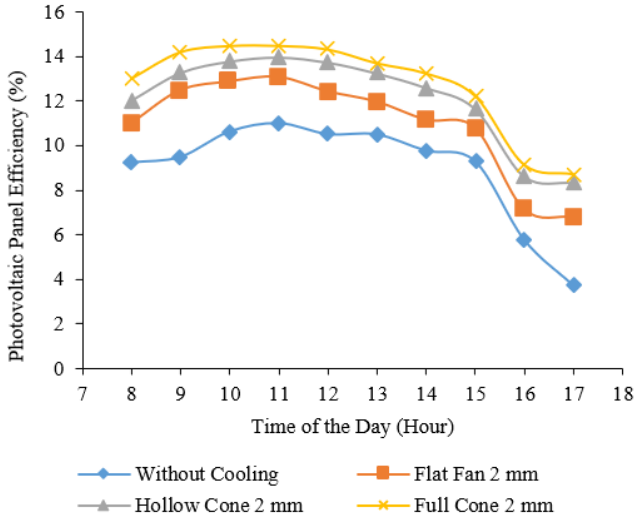

Figure 11. Photovoltaic panel efficiency over time throughout the day with nozzle diameter 2 mm

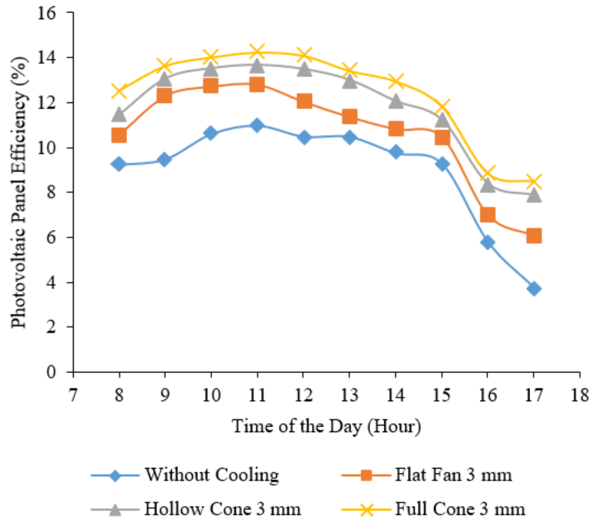

Figure 12. Photovoltaic panel efficiency over time throughout the day with nozzle diameter 3 mm

Figure 9 displays the I-V relationship, and Figure 10 illustrates the P-V relationship at 11:00 AM under a solar radiation intensity of 1000 W/m^2 for each nozzle type. Enhanced cooling positively impacts the generated power output, with *Pmpp* being higher when using a full cone nozzle than a flat fan nozzle and a hollow cone nozzle. The power output (*Pmpp*) results at 11:00 AM under a solar radiation intensity of 1000 W/m^2 using 2 mm diameter variations of flat fan nozzle, hollow cone nozzle, and full cone nozzle are 44.34 watts, 46.92 watts, and 48.65 watts, respectively. Conversely, for 3 mm diameter variations of these nozzles, the power output (*Pmpp*) results are 43.49 watts, 45.93 watts, and 47.85 watts. This difference in power output (*Pmpp*) between the total cone nozzle variation and the hollow cone and flat fan nozzle variations can be attributed to the lower operating temperature of the photovoltaic panel.

Figures 11 and 12 show the efficiency gains of photovoltaic panels throughout the day. The efficiency of the photovoltaic panel at 11:00 AM with a solar radiation intensity of 1000 W/m^2 using a full cone nozzle with a hole diameter of 2 mm is 14.47%. However, the efficiency results of photovoltaic panels with a hollow cone nozzle and a flat fan nozzle at 11:00 AM under a solar radiation intensity of 1000 W/m^2 and a hole diameter of 2 mm yielded lower results, precisely 13.95% and 13.05%. Furthermore, when photovoltaic panels were tested using a whole cone, hollow cone, and flat fan nozzles with a 3 mm diameter at 11:00 AM under a solar radiation intensity of 1000 W/m^2, the efficiency results were 14.23%, 13.66%, and 12.81%. These research findings demonstrate that employing a full cone nozzle in a water spray cooling system can lead to higher photovoltaic panel efficiency than using a hollow cone nozzle and a flat fan nozzle.

3.4 The effect of using different nozzle diameters in water spray cooling systems on the performance of photovoltaic panels

The difference in nozzle diameter in the water spray cooling system used results in different cooling performances for the photovoltaic panels. The large diameter of the nozzle hole affects the size of the water droplets produced. Based on the research results, a nozzle diameter of 2 mm can cool photovoltaic panels better than a nozzle diameter of 3 mm for each variation of nozzle type. Figure 13 shows a photovoltaic panel temperature graph at any time of the day with varying nozzle diameters. The research results for the water spray cooling system's impact on the temperature of photovoltaic panels with flat fan nozzle diameters of 2 mm and 3 mm at 11:00 AM under a solar radiation intensity of 1000 W/m^2 were 41.42°C and 42.07°C, respectively. The results of the water spray cooling system research on the temperature of photovoltaic panels with hollow cone nozzles with diameters of 2 mm and 3 mm at 11:00 AM under a solar radiation intensity of 1000 W/m^2 were 37.78°C and 38.84°C. The results of the water spray cooling system research on the temperature of photovoltaic panels with full cone nozzle diameters of 2 mm and 3 mm at 11:00 AM with a solar radiation intensity of 1000 W/m^2 were 36.27°C and 37.07°C.

Lower photovoltaic panel temperatures positively impact increasing power output and photovoltaic panel efficiency. Figure 14 shows a graph of photovoltaic panel efficiency at 08:00-17:00 with varying nozzle diameters. The highest efficiency was obtained with a nozzle diameter of 2 mm on a full cone nozzle, namely 14.47% at an intensity of 1000 W/m^2 in testing at 11:00 AM. Meanwhile, with the same time and type of nozzle, namely a sizeable full cone nozzle with a diameter of 3 mm, it produces 14.23%. The efficiency results of photovoltaic panels using hollow cone nozzles with hole diameters of 2 mm and 3 mm are 13.95% and 13.66%, respectively. Meanwhile, the efficiency results of photovoltaic panels with a flat fan nozzle and a diameter of 2 mm and 3 mm, respectively, are 13.05% and 12.81%. Obtaining photovoltaic panel efficiency results using a nozzle hole diameter of 2 mm obtained higher results than a nozzle diameter of 3 mm for each variation of nozzle type.

Obtaining better efficiency results due to better cooling can maximize the power output produced by photovoltaic panels. Using a nozzle diameter of 2 mm can produce better cooling results than a nozzle diameter of 3 mm because it can provide a more even spray of water on the surface of the photovoltaic panel with the same water discharge, namely 1.5 Lpm. Using the same water flow of 1.5 Lpm, a 3 mm diameter nozzle produces a weaker jet, leading to a less even distribution of the water spray on the surface of the photovoltaic panel compared to a 2 mm diameter nozzle. This is what makes the cooling results with a nozzle diameter of 2 mm more optimal for each variation of nozzle type, namely a flat fan nozzle, a hollow cone nozzle, and a full cone nozzle.

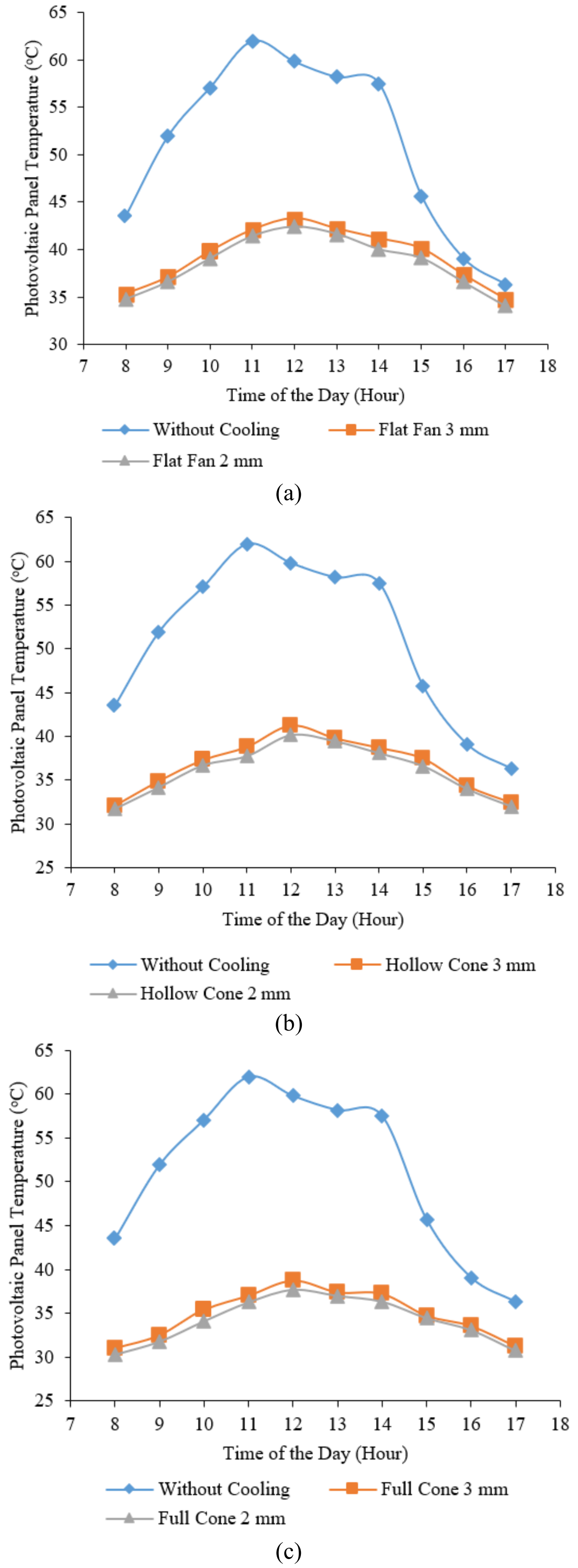

Figure 13. Graph of photovoltaic panel temperature against time throughout the day with nozzle types (a) Flat Fan nozzle, (b) Hollow cone nozzle, and (c) Full cone nozzle

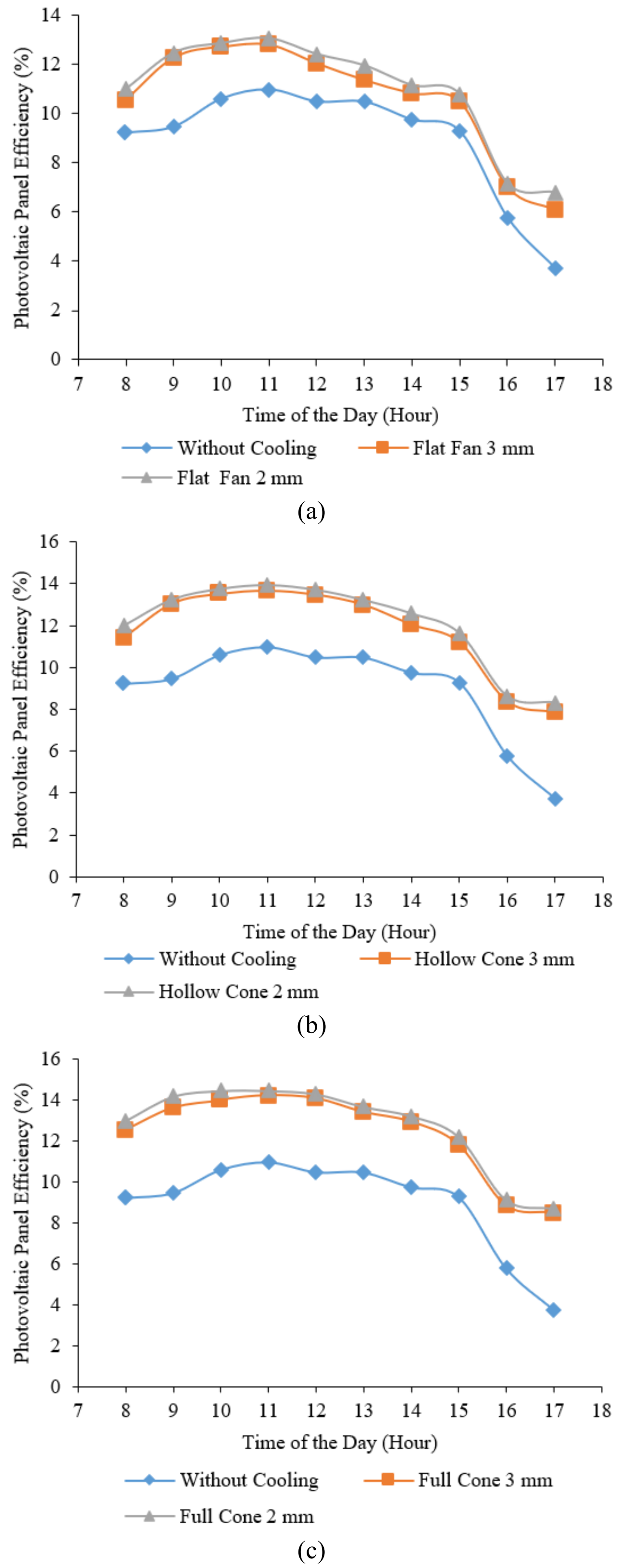

Figure 14. Graph of photovoltaic panel efficiency against time for each nozzle diameter variation with (a) Flat fan nozzle, (b) Hollow cone nozzle, and (c) Full cone nozzle

3.5 Uncertainty analysis

The accuracy value of the measuring instrument is required to calculate the uncertainty value, which is presented in Table 1. The equation used to calculate the uncertainty value for the photovoltaic panel efficiency value is as follows [22]:

$$W_R = \left[\left(\frac{\partial R}{\partial X_1} W_1\right)^2 + \left(\frac{\partial R}{\partial X_2} W_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial X_n} W_n\right)^2\right]^{0.5} \quad (7)$$

It is known that W_R results from uncertainty values with W_1, W_2, W_3, ..., and Wn being independent variables. The uncertainty value of photovoltaic panel efficiency is determined by entering variables that influence the efficiency value according to the efficiency summary in Eq. (6). So, it is known that the uncertainty value of photovoltaic panel efficiency is 5.85%.

4. CONCLUSION

The water spray cooling system on photovoltaic panels has been proven to reduce the temperature of photovoltaic panels, thereby increasing their power output and work efficiency. Photovoltaic panel temperature decreased from 61.96℃ to 36.51℃ and efficiency increased from 10.98% to 14.47% in testing at 11:00 AM with a solar radiation intensity of 1000 W/m^2.

The water spray cooling system with a full cone nozzle provides better cooling performance than a hollow cone and flat fan nozzles. Full cone nozzles can provide a more even spray of water that hits more of the surface of the photovoltaic panel, creating a more uniform temperature distribution. Different diameters for each type of nozzle provide different cooling performance. A nozzle diameter of 2 mm proves to be more effective in achieving enhanced cooling results when compared to a 3 mm diameter nozzle.

In this research, the entire cone nozzle configuration with a diameter of 2 mm had the best cooling performance, resulting in the highest efficiency of the photovoltaic panel. Cooling photovoltaic panels with water spray has a cooling solid performance and is easy to apply. For future research, further research can be carried out regarding the optimal time and duration for this active water spray cooling system to cool photovoltaic panels with the correct water flow, number of nozzles, and nozzle position.

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REFERENCES

[1] Kumar, M., Kumar, A. (2017). Performance assessment and degradation analysis of solar photovoltaic technologies: A review. Renewable and Sustainable Energy Reviews, 78: 554-587. https://doi.org/10.1016/j.rser.2017.04.083

[2] Hepbasli, A. (2008). A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future. Renewable and Sustainable Energy Reviews, 12(3): 593-661. https://doi.org/10.1016/j.rser.2006.10.001

[3] Arifin, Z., Prasetyo, S.D., Tjahjana, D.D.D.P., Rachmanto, R.A., Prabowo, A.R., Alfaiz, N.F. (2022). The application of TiO_2 nanofluids in photovoltaic thermal collector systems. Energy Reports, 8(s9): 1371–80. https://doi.org/10.1016/j.egyr.2022.08.070

[4] Salameh, T., Zhang, D., Juaidi, A., Alami, A.H., Al-Hinti, I., Olabi, A.G. (2021). Review of solar photovoltaic cooling systems technologies with environmental and economical assessment. Journal of Cleaner Production, 326: 129421. https://doi.org/10.1016/j.jclepro.2021.129421

[5] Alami, A.H., Ramadan, M., Abdelkareem, M.A., Alghawi, J.J., Alhattawi, N.T., Mohamad, H.A. (2022). Novel and practical photovoltaic applications. Thermal Science and Engineering Progress, 29: 101208. https://doi.org/10.1016/j.tsep.2022.101208

[6] Ghadikolaei, S.S.C. (2021). Solar photovoltaic cells performance improvement by cooling technology: An overall review. International Journal of Hydrogen Energy, 46(18): 10939–72. https://doi.org/10.1016/j.ijhydene.2020.12.164

[7] Skoplaki, E., Palyvos, J.A. (2009). On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. Solar Energy, 83(5): 614–624. https://doi.org/10.1016/j.solener.2008.10.008

[8] Prasetyo, S.D., Prabowo, A.R., Arifin, Z. (2023). The use of a hybrid photovoltaic/thermal (PV/T) collector system as a sustainable energy-harvest instrument in urban technology. Heliyon, 9(2): e13390. https://doi.org/10.1016/j.heliyon.2023.e13390

[9] Prasetyo, S.D., Prabowo, A.R., Arifin, Z. (2022). Investigation of thermal collector nanofluids to increase the efficiency of photovoltaic solar cells. International Journal of Heat and Technology, 40(2): 415–22. https://doi.org/10.18280/ijht.400208

[10] Mostakim, K., Hasanuzzaman, M. (2022). Global prospects, challenges and progress of photovoltaic thermal system. Sustainable Energy Technologies and Assessments, 53: 102426. https://doi.org/10.1016/j.seta.2022.102426

[11] Shoaib, M., Kakati, P., Dandotiya, D., M, U.R. (2022). A comprehensive review on various cooling techniques to decrease an operating temperature of solar photovoltaic panels. Energy Nexus, 8: 100161. https://doi.org/10.1016/j.nexus.2022.100161

[12] Mah, C.Y., Lim, B.H., Wong, C.W., Tan, M.H., Chong, K.K., Lai, A.C. (2019). Investigating the performance improvement of a photovoltaic system in a tropical climate using water cooling method. Energy Procedia, 159: 78–83. https://doi.org/10.1016/j.egypro.2018.12.022

[13] Ibrahim, M., Saeed, T. (2021). Designing a new heat sink containing nanofluid flow to cool a photovoltaic solar cell equipped with reflector. Journal of the Taiwan Institute of Chemical Engineers, 124: 9–16. https://doi.org/10.1016/j.jtice.2021.05.015

[14] Bahaidarah, H.M.S., Baloch, A.A.B., Gandhidasan, P. (2016). Uniform cooling of photovoltaic panels: A review. Renewable and Sustainable Energy Reviews, 57: 1520–1544. https://doi.org/10.1016/j.rser.2015.12.064

[15] Arifin, Z., Prasetyo, S.D., Prabowo, A.R., Tjahjana, D.D.D.P., Rachmanto, R.A. (2021). Effect of thermal collector configuration on the photovoltaic heat transfer performance with 3D CFD modeling. Open Engineering, 11(1): 1076–1085. https://doi.org/10.1515/eng-2021-0107

[16] Zhang, T., Wang, M., Yang, H. (2018). A review of the energy performance and life-cycle assessment of building-integrated photovoltaic (BIPV) systems. Energies, 11(11): 3157. https://doi.org/10.3390/en11113157
[17] Hernandez-Perez, J.G., Carrillo, J.G., Bassam, A., Flota-Banuelos, M., Patino-Lopez, L.D. (2021). Thermal performance of a discontinuous finned heatsink profile for PV passive cooling. Applied Thermal Engineering, 184: 116238. https://doi.org/10.1016/j.applthermaleng.2020.116238
[18] Arifin, Z., Prasetyo, S.D., Tribhuwana, B.A., Tjahjana, D.D.D.P., Rachmanto, R.A., Kristiawan, B. (2022). Photovoltaic performance improvement with phase change material cooling treatment. International Journal of Heat and Technology, 40(4): 953–60. https://doi.org/10.18280/ijht.400412
[19] Razali, S.N., Ibrahim, A., Fazlizan, A., Fauzan, M.F., Ajeel, R.K., Zairah Ahmad, E. (2023). Performance enhancement of photovoltaic modules with passive cooling multidirectional tapered fin heat sinks (MTFHS). Case Studies in Thermal Engineering, 50: 103400. https://doi.org/10.1016/j.csite.2023.103400
[20] Nižetić, S., Čoko, D., Yadav, A., Grubišić-Čabo, F. (2016). Water spray cooling technique applied on a photovoltaic panel: The performance response. Energy Conversion and Management, 108: 287–296. https://doi.org/10.1016/j.enconman.2015.10.079
[21] Raju, M., Sarma, R.N., Suryan, A., Nair, P.P., Nižetić, S. (2022). Investigation of optimal water utilization for water spray cooled photovoltaic panel: A three-dimensional computational study. Sustainable Energy Technologies and Assessments, 51: 101975. https://doi.org/10.1016/j.seta.2022.101975
[22] Yesildal, F., Ozakin, A.N., Yakut, K. (2022). Optimization of operational parameters for a photovoltaic panel cooled by spray cooling. Engineering Science and Technology, an International Journal, 25: 100983. https://doi.org/10.1016/j.jestch.2021.04.002
[23] Jiang, L.J., Jiang, S.L., Cheng, W.L., Nian, Y.L, Zhao, R. (2019). Experimental study on heat transfer performance of a novel compact spray cooling module. Applied Thermal Engineering, 154: 150–156. https://doi.org/10.1016/j.applthermaleng.2019.03.078
[24] Moharram, K.A., Abd-Elhady, M.S., Kandil, H.A., El-Sherif, H. (2013). Influence of cleaning using water and surfactants on the performance of photovoltaic panels. Energy Conversion and Management, 68: 266–272. https://doi.org/10.1016/j.enconman.2013.01.022
[25] Kazem, H.A., Chaichan, M.T., Al-Waeli, A.H.A., Sopian, K. (2022). Effect of dust and cleaning methods on mono and polycrystalline solar photovoltaic performance: An indoor experimental study. Solar Energy, 236: 626–643. https://doi.org/10.1016/j.solener.2022.03.009
[26] Ekinci, F., Yavuzdeğer, A., Nazlıgül, H., Esenboğa, B., Doğru Mert, B., Demirdelen, T. (2022). Experimental investigation on solar PV panel dust cleaning with solution method. Solar Energy, 237: 1-10. https://doi.org/10.1016/j.solener.2022.03.066
[27] Prasetyo, S.D., Budiana, E.P., Prabowo, A.R., Arifin, Z. (2023). Modeling finned thermal collector construction nanofluid-based AL2O3 to enhance photovoltaic performance. Civil Engineering Journal, 9(12): 2989-3007. https://doi.org/10.1016/j.enconman.2013.01.022
[28] Chen, H., Wang, Y., Yang, H., Badiei, A., Li, G. (2022). Experimental investigation and exergy analysis of a high concentrating photovoltaic system integrated with spray cooling. Energy Conversion and Management, 268: 115957. https://doi.org/10.1016/j.enconman.2022.115957
[29] Bevilacqua, P., Bruno, R., Rollo, A., Ferraro, V. (2022). A novel thermal model for PV panels with back surface spray cooling. Energy, 255: 124401. https://doi.org/10.1016/j.energy.2022.124401
[30] Zhao, Y., Gong, S., Zhang, C., Ge, M., Xie, L. (2022). Performance analysis of a solar photovoltaic power generation system with spray cooling. Case Studies in Thermal Engineering, 29: 101723. https://doi.org/10.1016/j.csite.2021.101723
[31] Javidan, M., Moghadam, A.J. (2021). Experimental investigation on thermal management of a photovoltaic module using water-jet impingement cooling. Energy Conversion and Management, 228: 113686. https://doi.org/10.1016/j.enconman.2020.113686
[32] Laseinde, O.T., Ramere, M.D. (2021). Efficiency Improvement in polycrystalline solar panel using thermal control water spraying cooling. Procedia Computer Science, 180: 239–248. https://doi.org/10.1016/j.procs.2021.01.161
[33] Hadipour, A., Rajabi Zargarabadi, M., Rashidi, S. (2021). An efficient pulsed- spray water cooling system for photovoltaic panels: Experimental study and cost analysis. Renewable Energy, 164: 867–875. https://doi.org/10.1016/j.renene.2020.09.021
[34] Yang, L.H., Liang, J. De, Hsu, C.Y., Yang, T.H., Chen, S.L. (2019). Enhanced efficiency of photovoltaic panels by integrating a spray cooling system with shallow geothermal energy heat exchanger. Renewable Energy, 134: 970–981. https://doi.org/10.1016/j.renene.2018.11.089
[35] Sun, T., Huang, X., Chen, Y., Zhang, H. (2020). Experimental investigation of water spraying in an indirect evaporative cooler from nozzle type and spray strategy perspectives. Energy and Buildings, 214: 109871. https://doi.org/10.1016/j.enbuild.2020.109871
[36] Jin, Q., Yu, Y., Zhang, J. (2023). Numerical and experimental study on intermittent spray cooling for plate-fin heat exchanger. Applied Thermal Engineering, 234: 121328. https://doi.org/10.1016/j.applthermaleng.2023.121328
[37] Somasundar, K.G., Soorej, S., Karthikeyan, S., Jayan, N., Bhatlu, M.L.D. (2020). Review on cooling tower nozzle types. Materials Today: Proceedings, 37: 3016-3018. https://doi.org/10.1016/j.matpr.2020.08.723
[38] Chen, H., Ruan, X.H., Peng, Y.H., Wang, Y.L., Yu, C.K. (2022). Application status and prospect of spray cooling in electronics and energy conversion industries. Sustainable Energy Technologies and Assessments, 52: 102181. https://doi.org/10.1016/j.seta.2022.102181
[39] Arifin, Z., Tjahjana, D.D.D.P., Hadi, S., Rachmanto, R.A., Setyohandoko, G., Sutanto, B. (2020). Numerical and experimental investigation of air cooling for photovoltaic panels using aluminum heat sinks. International Journal of Photoenergy, 2020: 1574274. https://doi.org/10.1155/2020/1574274
[40] Suman, S.P., Goyal, P. (2021). Analysing the effects of solar insolation and temperature on PV cell

characteristics. Materials Today: Proceedings, 45: 5539-5543. https://doi.org/10.1016/j.matpr.2021.02.301

[41] Arifin, Z., Nurachim, Z., Hadi, S., Rachmanto, R.A., Prasetyo, S.D. (2022). The effect of additional air deflector at air concentrator on photovoltaic performance. Mathematical Modelling of Engineering Problems, 9(5): 1399–1405. https://doi.org/10.18280/mmep.090531

[42] Al-Shahri, O.A., Ismail, F.B., Hannan, M.A., Lipu, M.S.H., Al-Shetwi, A.Q., Begum, R.A. (2021). Solar photovoltaic energy optimization methods, challenges and issues: A comprehensive review. Journal of Cleaner Production, 284: 125465. https://doi.org/10.1016/j.jclepro.2020.125465

[43] Hysa, A. (2019). Modeling and simulation of the photovoltaic cells for different values of physical and environmental parameters. Emerging Science Journal, 3(6): 395–406. https://doi.org/10.28991/esj-2019-01202

NOMENCLATURE

I_{SC}	Short circuit current (A)
V	Photovoltaic panel output voltage (V)
V_{OC}	Open circuit voltage (V)
V_T	Thermal voltage (V)
M	Diode ideality factor
G	Solar radiation on site (W/m^2)
G^r	Solar radiation at Standard Test Conditions (STC) (W/m^2)
I_{MPP}^r	Maximum current at STC (A)
I_{MPP}	Maximum current (A)
I_0	Saturation current (mA)
FF	Fill Factor
I_{light}	Power of solar radiation (W/m^2)
I_{rad}	The intensity of sunlight (W/m^2)
A	The active area of the solar cell (m^2)
P_{MPP}	Maximum power (Watt)
W_R	Uncertainty

Greek symbols

η	Efficiency (%)