EFFECT OF FILM WATER-COOLING ON THE ELECTRICAL PERFORMANCE EFFICIENCY OF A SOLAR PV MODULE

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Abstract: *High operating temperatures significantly reduce the performance efficiency of solar photovoltaic (PV) modules, especially in hot climates regions. This study experimentally investigates the effect of film water-cooling on the electrical performance of a solar PV module under Sokoto State climatic conditions, Nigeria. Key environmental parameters, including solar irradiance, ambient temperature, wind speed, and module temperature, were measured over five consecutive days. A gravity-fed system was used to form a thin film of water over the module surface at a controlled flow rate. Electrical parameters such as voltage and current were recorded to calculate output power and then evaluate efficiency. Results show that film water-cooling reduced module temperature and improved electrical efficiency, achieving a peak value of 10.5% compared to natural air-cooling. The practical findings demonstrate that film water cooling is a simple, effective, and low-cost method for improving PV performance in hot regions.*

Keywords: *electrical efficiency, film water-cooling, natural air-cooling, performance optimization, renewable energy, solar PV module, temperature effect*

1. INTRODUCTION

Energy enhances manufacturing, mining, commerce, business, communication, transportation, industry, agriculture, public health, quality education, life skill, working experience, and environmental security. Briefly, it enriches life in which no nation can survive without it" (Osanyinpeju et al., 2018).

Solar energy is alternative to fossil fuels. It is renewable, sustainable, accessible, affordable, and environmentally friendly. It can be used continuously without any notable negative impact (Carl von, 2012). Significantly, our world gravitates towards producing and utilizing the renewable forms of energy in a more sustainable and friendly manner (Okereke et al., 2020).

Solar photovoltaic (PV) module is a device that converts solar energy into electrical energy. it is widely used for electricity generation (Kumar, 2025). Its working principle can simply be described as when sunlight hits the cells of the module, then the solar energy will knock electrons of the silicon material, leading to electrons movement. Such free electrons will continuously flow, creating electricity in form of direct current (D.C) (Waaree, 2024).

For the brief historical development, the underlying principle behind the conversion of sunlight into solar energy is photovoltaic (PV) effect, which was first observed in 1839 by Alexander Edmund Becquerel (Yadav & Kumar, 2015). The practical solar PV Cell was first introduced by Russel Ohl in 1946 (Castellano, 2010). The materials used in designation and construction of solar PV module are semiconductor materials such as single-crystal, amorphous-silicon, and multi-crystalline (Bagher et al., 2015; Srinivas et al., 2015). Figure 1 demonstrated the technology behind the PV module (Schüler, 2018)

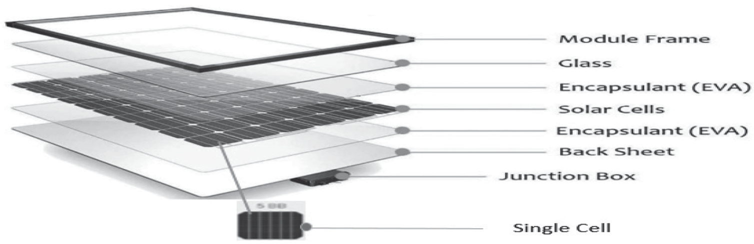

Figure 1: Technology of Solar Photovoltaic (PV) Module

However, PV module is very sensitive to temperature. Increased temperature leads to reduced its voltage output and overall efficiency, thereby limiting its energy yield. This effect is more pronounced in hot climatic regions with high solar irradiance. The performance of solar PV is significantly affected by operating temperature (Hasan et al., 2021).

Various cooling techniques have been proposed to mitigate this issue, including air cooling, water cooling, and hybrid systems. Among the other method, film water-cooling—where a thin layer of water flows over the module surface—has been identified as an effective and low-cost method for heat removal (Dwivedi et al., 2020).

Film water-cooling method is a very simple and cost-effective technique to mitigate heat accumulation and enhance electrical performance. It is an effective strategy for maintaining lower operating temperatures, especially suitable for hot climates, due to its high heat removal capacity and simplicity of implementation. Water has a high cooling capacity with high thermal conductivity (Moharram et al., 2013)

Despite extensive research on PV cooling techniques, there is limited experimental data on low-cost film water-cooling systems under extreme climatic conditions such as those in Sokoto, Nigeria, which is located within a very high-sunshine region with an annual average daily sunlight of 6.25

hours, ranging between approximately 3.5 hours at the coastal sections and 9.0 hours at the far northern boundary" (Osueke & Ezugwu, 2011).

Furthermore, many studies lack integrated analysis of environmental parameters and statistical validation of performance improvement. For instance, the level solar integration status in Nigeria is difficult to evaluate due to the insufficient detailed information about their solar energy technology, projects, and capacity (Bamisile et al., 2017).

The main aim of this research work (study) is to experimentally investigate the impact of film water-cooling on the electrical efficiency of PV modules under the climatic conditions of Sokoto State, Nigeria, incorporating electrical and environmental measurements. Objectively, a data collection, solar power calculation, and then electrical efficiency evaluation will be conducted with proper experimental setup for natural air- and film water-cooling modules. Significantly, it can provide a practical insight for PV system optimization in regions with high solar irradiance.

2. MATERIALS AND METHODS

2.1. Selection of Materials

For the experimental research work, the materials used are two identical PV modules, obtained at Sokoto Energy obtained at Sokoto Energy Research Center (SERC), UDUS. While the others materials are water container, PVC pipe, solar power meter, digital multimeters, infrared thermometer, anemometer, meter rule and digital stopwatch, obtained at Ranganda market place.

Table 1: Specifications of materials

S/N	Names of Materials	Specifications
1	Two identical PV Modules	SUNSHINE SOLAR (P_{max} = 180W, V_{mp} = 18.1V, I_{mp} = 9.95A, V_{oc} = 22.26V, & I_{sc} = 10.63A)
2	Water Container	15-liter (0.5-liter X 30)
3	PVC Pipe	50 cm with 3 mm holes
4	Solar Power Meter	SL102, Di-LOG
5	Digital Multimeters	DT9205A, ANENG
6	Digital Infrared Thermometer	GM320 IR, BENETECH
7	Digital Anemometer	TAB161, TASi

2.2. Methods

2.2.1. Design and Construction of Experimental Setup

Figure 2 shown two PV modules installed side by side. One of the modules was cooled by allowing a film water from a container to flow over its surface through a 50cm PVC pipe with 3 mm holes. The other module was cooled by allowing an ambient air to flow over its surface.

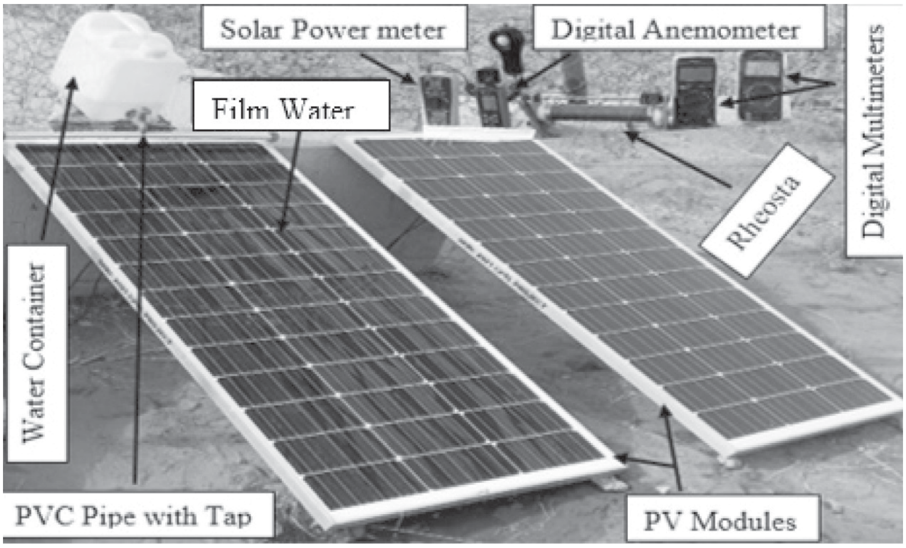

Figure 2: Experimental setup for natural air- cooling and film water-cooling modules

2.2.2. Measurements and Data Collection

Two digital Multimeters were connected to each module: one in parallel to measure voltage, and the other in series to measure current. A solar power meter was used to measure solar irradiances (I_s). A plastic meter rule was used to measure the length & breadth of the individual cell. The anemometer was used to measure the wind speed, and and ambient temperature. Finally, the modules' and cooling mediums' temperature were measured using infrared thermometer.

2.2.3. Calculations of Solar input and output powers

The input solar power (P_{in}) was calculated using the model given by Sengupta et al., (2018) as:

$P_{in} = I_s . A_f$ .... (1)

And the model used for the modules' effective area () was given by Energypedia (2024) as;

$A_f = n_c$ X $a_c = 0.8m^2$ .... (2)

Where: I_s = *Solar irradiance (W/m²)* n_c = 36, number cells, and a_c = 0.022m^2, area of each cell.

The model used for output electrical power (P_{out}) was given by Electrical Technology (2020), as:

$P_{out} = V_{max}$ x I_{max} .... (3)

Where: V_{max} = *maximum voltage (V) and* I_{max} = *maximum current (A)*

2.2.4. Evaluation of Electrical Performance Efficiency

Electrical efficiency (η_{el}) demonstrates the quantity of power can be provided under certain environmental conditions. It can be evaluated using model given by Agyekum et al (2021), as:

$$\eta_{el} = \frac{P_{out}}{P_{in}} \text{ x } 100\% \quad \ldots\ldots\ldots\ldots \quad (4)$$

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Experimental Setup

The experimental research work, properly setup on unobstructed sunlight area, was conducted at Sokoto Energy Research Center (SERC). For the film water-cooling module, the unrecycled water flow rate was maintained at approximately 0.5 L per minute using a gravity-fed system. To maximize the solar energy, the modules were positioned at tilt angle of approximately 3° facing north, as optimal for Sokoto State during a summer (Robinson, 2024).

3.2. Measured Experimental Data

Table 2 presents the recorded environmental parameters, including solar irradiance; I_s (ms^{-1}), ambient temperature; θ_a (^{o}C), wind speed; V_W (ms^{-1}), and temperature for natural air (θ_n) and film water cooling modules (θ_f). Table 3 presents the recorded experimental parameters, included modules' open circuited voltage (**V_{oc}**); short circuited current (**I_{sc}**); and maximum voltage (I_{max}) and current (V_{max}) for natural air (**N_{ac}**) and film water cooling (**F_{wc}**).

Table 2: Measured, averaged, and recorded environmental parameters

Time (min)	θ_a (^{o}C)	I_s (ms^{-1})	V_W (ms^{-1})	θ_n (^{o}C)	θ_f (^{o}C)
8:30am	29.7	446.2	0.2	37.7	37.6
9:00am	34.5	446.2	0.3	45.9	40.2
9:30am	36.1	480.2	0.4	49.5	44.6
10:00am	32.2	563	0.6	49.4	44.0
10:30am	31.9	558	0.4	56.2	47.7
11:00am	32.7	596.8	0.5	57.5	42.5
11:30am	35.0	567.2	0.3	55.3	49.1
12:00pm	34.8	554.6	0.4	59.4	51.8
12:30pm	34.3	578.2	0.6	57.1	47.1
1:00pm	34.9	605.2	0.8	53.6	46.8
1:30pm	34.4	523.8	0.8	61.6	49.5
2:00pm	35.1	546.2	0.6	60.0	44.8
2:30pm	34.8	575.4	0.1	60.4	46.5
3:00pm	35.6	575.6	0.3	57.9	48.2
3:300pm	36.3	518	0.3	55.7	44.9
4:00pm	36.5	474.4	0.5	51.5	41.2
4:30pm	36.0	412.6	0.5	46.3	41.6
5:00pm	34.7	399	0.3	37.9	39.5

The Voltages and currents values were obtained at rheostat settings (9 and 18). All the instruments used in the research work were calibrated according to manufacturer specifications before use. The measurements were taken simultaneously after every 30s, from 8:00 am to 5:00 pm, over five consecutive days, for a diurnal variation (Ji et.al., 2021).

Table 3: Measured, averaged, and recorded experimental parameters

Time (min)	V_{oc} (volt)		I_{sc} (A)		I_{max} (A)		V_{max} (volt)	
	$\mathbf{N_{ac}}$	$\mathbf{F_{wc}}$	$\mathbf{N_{ac}}$	$\mathbf{F_{wc}}$	$\mathbf{N_{ac}}$	$\mathbf{F_{wc}}$	$\mathbf{N_{ac}}$	$\mathbf{F_{wc}}$
8:30am	13.5	16	4.8	4.2	1.6	1.9	17.4	17.8
9:00am	15.8	17.4	5.1	4.8	1.6	1.8	17.8	18.6
9:30am	21.2	20.2	6.0	5.7	1.5	1.9	18.7	19.1
10:00am	21.9	20.7	7.0	6.9	1.6	1.7	20.3	21.2
10:30am	20.8	20.7	7.5	7.7	1.6	1.7	19.6	20.1
11:00am	19	20.6	7.0	7.8	1.6	1.7	19.1	19.6
11:30am	20.5	21.6	8.7	9.6	1.6	1.7	19.7	19.8
12:00pm	21.1	20	8.3	8.5	1.6	1.7	19.8	19.5
12:30pm	17.7	20	7.5	8.3	1.6	1.7	19.0	20.1
1:00pm	17.4	19.8	7.2	7.2	1.6	1.7	19.2	20.3
1:30pm	17.7	18.3	7.0	7.5	1.6	1.7	18.9	18.8
2:00pm	17.6	15.4	6.6	6.6	1.6	1.7	17.1	16.9
2:30pm	18.2	18.3	6.3	18.7	1.6	1.7	17.7	17.5
3:00pm	19.9	17.9	4.8	4.8	1.5	1.7	16.2	17.2
3:30pm	17.1	17.7	3.1	3.4	1.5	1.7	15.9	16.2
4:00pm	15.8	18.5	2.1	2.0	1.4	1.6	17.4	15.8
4:30pm	14.6	19.4	1.8	1.4	1.5	1.5	16.6	15.1
5:00pm	15.8	20.8	1.6	1.1	1.3	1.3	16.4	14.2

3.3. Input and Output Solar Power

The solar input and output power, for the five (5) consecutive days over the given time, were calculated. The performance efficiencies of each of the cooling module were then evaluated. Numerically, the results of the both powers and efficiencies, for the natural air- and film water-cooling, modules were recorded in Table 4. Since the voltages and currents values were obtained at fixed resistive loads; therefore, the calculated output power represents an approximation and not the exact maximum power point (MPP).

Table 4: Solar input and output power, and efficiency of each of the cooling module

Time	Input Power	Natural Air-Cooling Module		Film Water-Cooling Module	
		Output Power	Electrical Efficiency	Output Power	Electrical Efficiency
8:30am	356.8	28.26	8.06	29.3	10.52
9:00am	384.2	28.2	7.32	31.16	8.8
9:30am	450.4	27.1	6.04	31.18	7.78
10:00am	446.2	32.88	7.44	35.64	7.62
10:30am	477.4	31.44	6.62	33.18	7.34
11:00am	453.8	30.78	6.8	32.36	7.66
11:30am	443.8	31.2	7.52	32.68	8.88
12:00pm	462.4	31.24	6.8	32.16	7.52
12:30pm	484.2	30.18	6.28	33.62	6.9
1:00pm	419	30.64	7.34	33.7	8.08
1:30pm	436.8	30.24	6.96	32.38	7.66
2:00pm	460.4	27.2	5.9	28.16	6.22
2:30pm	460.4	28.02	6.06	28.98	6.48
3:00pm	414.4	24.84	6.02	24.02	6.98
3:300pm	379.6	24.52	7.08	24.58	8.14
4:00pm	330	23.84	7.34	23.6	8.92
4:30pm	322.8	24.3	7.9	18.34	8.42
5:00pm	250.2	21.08	8.52	14.52	8.36

Figure 3 presents a variation between the solar irradiance (**I_S**) and input power (**P_i**)

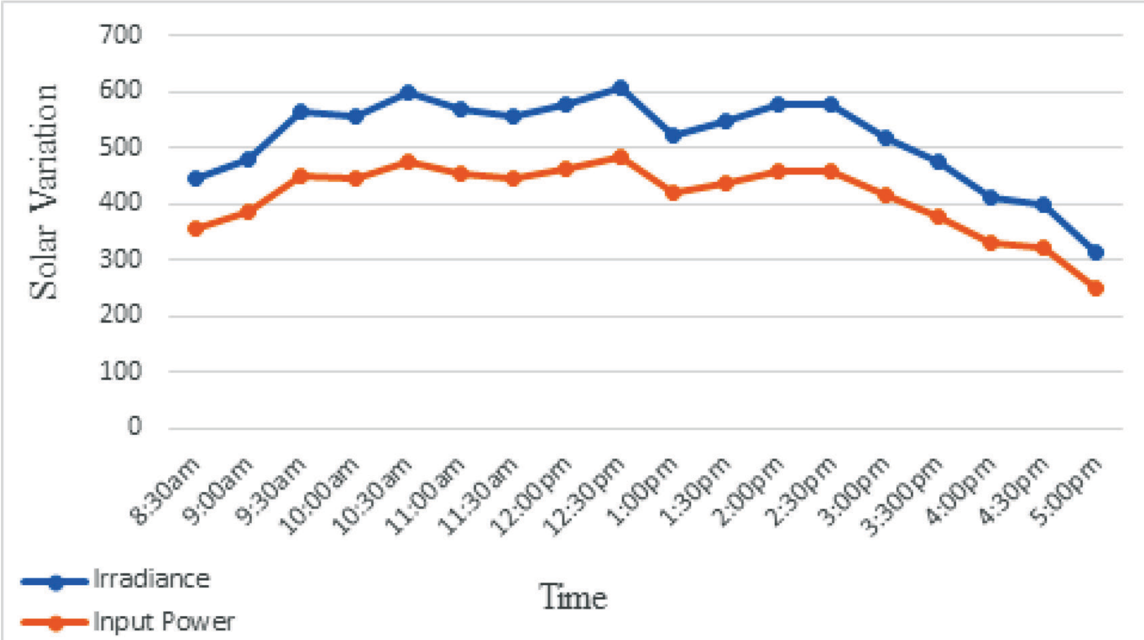

Figure 3: Variation of solar irradiance and input power over a time

The graph of figure 3 showed that the highest value reached by both $\mathbf{I}_S$ and $\mathbf{P}_i$, at 12:30 P.M., was 605.2 W/m^2 and 484.2 W respectively. The $\mathbf{P}_i$ increased as the $\mathbf{I}_S$ increased and vice versa. These results clearly demonstrated a direct relationship between $\mathbf{I}_S$ and $\mathbf{P}_i$,. It demonstrated the effectiveness of solar irradiance on solar input power.

Figure 4 presents an average solar output power under two cooling techniques over a time. From the graph, the film water-cooling module showed a higher output power ($\mathbf{P}o\mathbf{.av}_w$), reached up to 35.64 W, while the natural air-cooling ($\mathbf{P}o\mathbf{.av}_n$) showed the lowest output power, reaching up to

32.88 W, both at 10:00 am. Compared to natural air-cooling control module, the film water -cooling module displayed more improved output power throughout the experimental days.

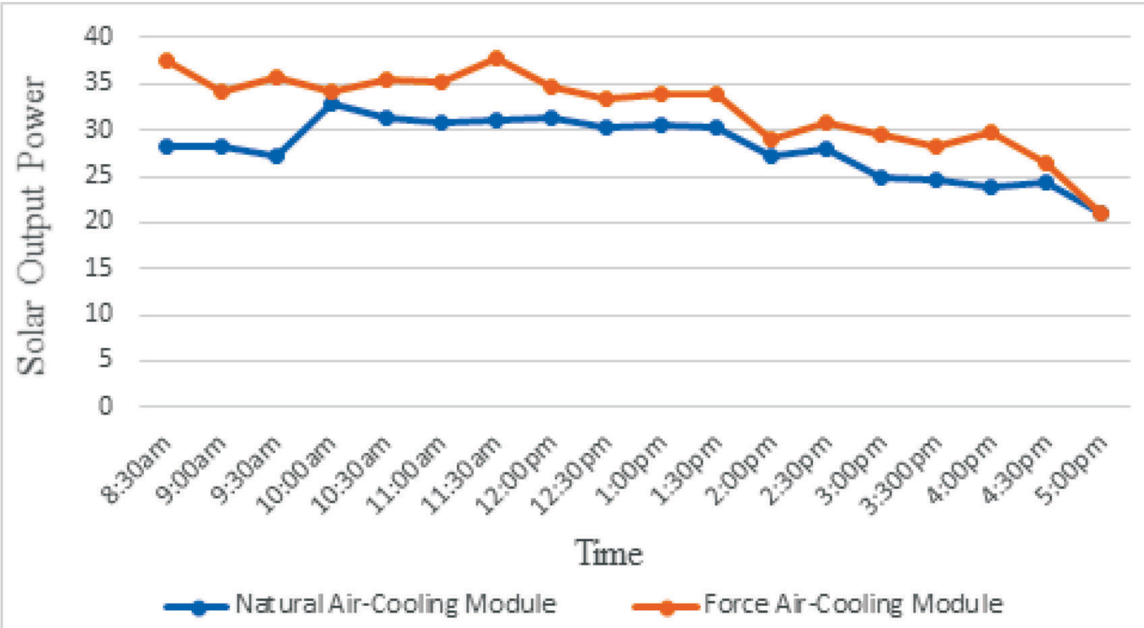

Figure 4: Solar output power of two different cooling modules over the time

3.4. Electrical Performance Efficiency Trends

The graph of Figure 5 presents a variation of performance efficiency between two different cooling modules over a time. As recorded in Table 4, compared to the natural air-cooling module, the film water-cooling module consistently produced an improved electrical efficiency (reached the highest of 10.5% at 8:30am).

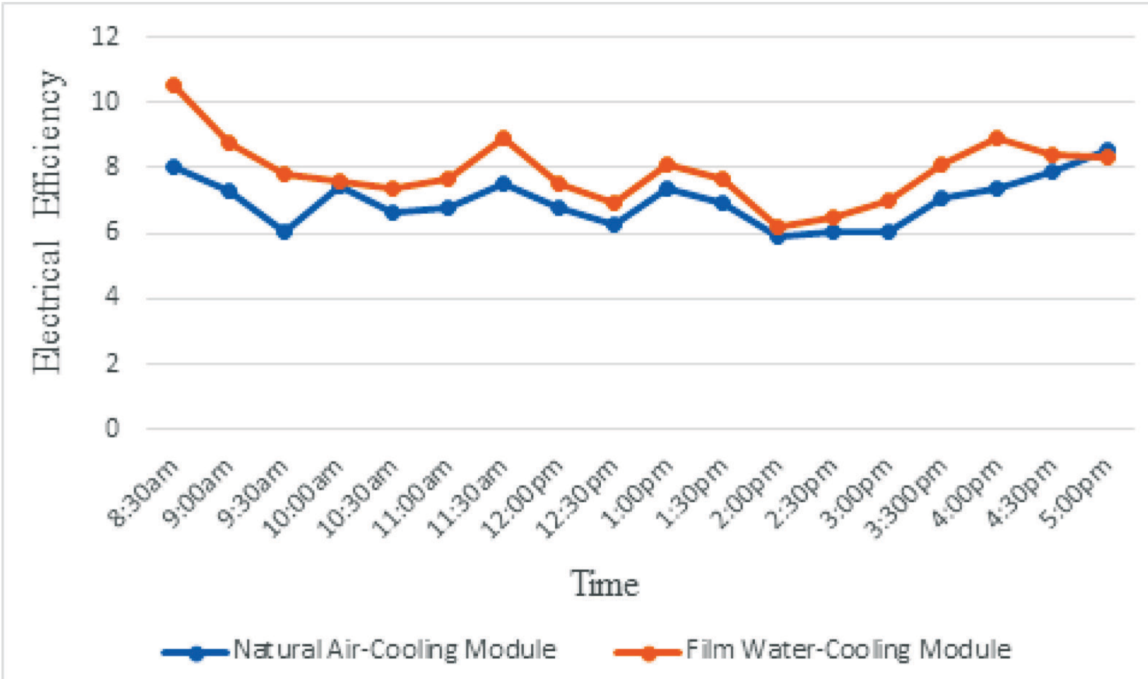

Figure 5: Comparison between the efficiency of two cooling modules over a time

3.5. Environmental Analysis

As showed in the graph, in the early morning and late afternoon, the efficiencies of the modules were high due to reduced irradiance and cooling impact, demonstrating a low input power with high output energy. Film water-cooling consistently produced a higher efficiency compared to the natural air-cooling. A peak efficiency of 10.5% was recorded for the water-cooled module.

3.6. Temperature Analysis

At peak conditions, the film water-cooling system significantly reduced the PV module temperature compared to natural air-cooling whose peak module temperatures exceeded 60°C. The reduction contributed to improved electrical efficiency due to increased voltage output. At low solar irradiance conditions (in late afternoon), the cooling effect becomes less beneficial because the module temperature is already reduced naturally. The water-cooled module exhibited lower performance than the natural air-cooled module. Therefore, this result confirmed that temperature reduction plays a critical role in PV performance improvement. It is also attributed to reduced benefit of cooling at lower temperature.

3.7. Statistical Analysis

Table 5 showed Comparative Summary for the Electrical Efficiency of each of the Cooling Methods. From the table, the electrical efficiency of the film water-cooling module, ranged between 6.2 to 10.5, was greater than that of the natural air-cooling module, ranged between 5.9 to 8.5. Similarly, the sum, mean, and variance of the electrical efficiency of the film water-cooling, which are 132, 7.3, and 1.16 respectively, were also greater than that of the natural air-cooling module, which are 126; 7; and 0.57 respectively. Therefore, these analyses showed that there is a statistically significant differences between the efficiency of the two cooling methods, confirming that the observed improvements are not only due to random variation.

Table 5: Comparative Summary for the Electrical Efficiency of each of the Cooling Methods

Cooling Methods	Efficiencies' Range	Sum	Mean	Variance
Natural Air	5.9 – 8.5	126	7.0	0.57
Film Water	6.2 – 10.5	132	7.3	1.16

4. DISCUSSION

The results clearly show that film water-cooling improves the electrical performance of PV modules by reducing operating temperature. Lower module temperatures reduce resistive losses and improve voltage output, which directly enhances efficiency. The effectiveness of the cooling system varies throughout the day due to changes in solar irradiance and environmental conditions.

At peak irradiance, the cooling effect is more significant, leading to higher performance gains. However, at low irradiance conditions (late afternoon), the advantage of cooling decreases because the module temperature is already reduced naturally. In addition, the presence of a water film may introduce optical losses due to reflection and absorption, which can reduce incident solar radiation. These findings are consistent with previous studies on PV cooling systems and confirm that temperature control is a key factor in improving PV efficiency (Hasan et al., 2021).

5. CONCLUSION

This study demonstrates that film water-cooling significantly improves the electrical performance of solar PV modules under hot climatic conditions. The film water-cooling system effectively reduced module temperature, improved output power, and enhanced electrical efficiency, achieving a peak value of 10.5%. The results confirm that temperature reduction plays a critical role in improving PV performance. Film water-cooling is therefore a simple, viable, and low-cost solution for enhancing solar energy systems in high-temperature regions.

Recommendation for Future Work

• Integration of water recycling systems

• Exploration of hybrid cooling techniques (like water + air)

• investigation of Long-term performance analysis

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