STUDY ON ENHANCING THE EFFICIENCY OF SOLAR PANELS USING CONDENSATE WATER RECOVERED FROM AIR CONDITIONER EVAPORATOR

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Abstract - Under the tropical climate conditions of Ho Chi Minh City, the average ambient temperature of approximately 35.6°C causes the surface temperature of photovoltaic (PV) panels to gradually rise from 45°C ± 2°C under solar irradiance levels ranging from 800 to 1000 W/m², thereby reducing the system's efficiency and durability. This study applies an active cooling solution using forced water spraying, in which domestic water (25–30°C) is mixed with condensate water from air-conditioning evaporator units (10–15°C) to produce a cooling source with a temperature range of 17.5–22.5°C. The experimental model shows that this method maintains a conversion efficiency of approximately η ≈ 19.5% to 20.08 and a power output close to the theoretical value, outperforming natural convection (~18.15%). The results demonstrate the feasibility of the mixed-water cooling system under hot and humid climatic conditions, contributing to improved energy harvesting efficiency and enhanced operational stability of the PV panels.

Key words - PV modules; solar energy; photovoltaic efficiency; solar panel cooling; renewable energy

1. Introduction

Photovoltaic (PV) modules essentially operate as photodiodes, in which a large-area p–n junction generates a photovoltage under incident photon radiation. At the application scale, PV modules are commonly interconnected in series and/or parallel configurations to achieve the required voltage and power levels, thereby forming solar panels or photovoltaic power systems of various scales. Silicon semiconductor materials - in monocrystalline, polycrystalline, or amorphous forms - currently dominate the commercial market [1], [2]. Studies indicate that the electrical efficiency of crystalline-silicon PV modules typically reaches only 15–20% and decreases by approximately 0.3–0.5% for each 1°C increase in temperature [3]. However, when integrated into photovoltaic–thermal (PVT) systems, excess heat can be recovered, helping to maintain the cell temperature 10–20°C lower than that of conventional PV modules, thereby enhancing electrical efficiency and providing an additional thermal efficiency of 40–70%. The overall efficiency of PVT systems can reach 60–85%, which is superior to that of standalone PV modules [3].

The electrical and optical properties of silicon are highly sensitive to temperature variations. The efficiency of amorphous-silicon PV modules decreases markedly as temperature increases due to increased leakage current and capacitance; the open-circuit voltage V_{oc} decreases (≈ –2 mV °C^{-1}), while the short-circuit current I_{sc} increases slightly (+0.1% °C^{-1}), resulting in a power derating coefficient of –0.35%/°C [4]. Research findings [5], [6] show that, as temperature rises, I_{sc} increases only marginally whereas V_{oc} decreases significantly, leading to a reduction in the maximum power P_{max} and conversion efficiency. Quantitatively, I_{sc} increases by approximately 0.1% per °C due to bandgap narrowing, while V_{oc} decreases on average by 2 mV °C^{-1}, causing the overall module efficiency to decline by 0.3–0.5 % °C^{-1} depending on the cell type [7]. This degradation directly affects system lifetime and operational stability; therefore, temperature control becomes a critical challenge. Another solution that has attracted attention is the utilization of condensate water from air-conditioner evaporators, combined with municipal water, to form a recirculating water source for cooling PV panels. This approach is novel in that it not only maintains the operating temperature within an optimal range but also effectively leverages a readily available water source in air-conditioning systems, thereby improving the reliability, efficiency, and sustainability of photovoltaic power systems.

2. Theoretical background

2.1. Effect of PV Temperature on PV Efficiency

After applying a water-based cooling solution, the efficiency of a PV panel can be evaluated through the relationship between efficiency and the panel operating temperature. The PV efficiency at the water-cooled operating temperature is determined by the following expression [4]:

$$\eta_{T(water)} = \eta_{ref} \times [1 - \gamma_{ref} \times (T - T_{ref})] \ (\%) \quad (1)$$

where:

η_T: temperature-dependent electrical efficiency (%);

η_{ref}: efficiency at the reference condition T_{ref} = 25°C, and total irradiance G_T = 1 kW/m^2;

γ^{ref}: temperature coefficient of efficiency (% K^{-1});

T: PV panel surface temperature (°C);

T_{ref}: reference temperature (°C).

The above equation reflects the linear decreasing trend of PV efficiency as the operating temperature increases relative to the standard condition. When water cooling is applied, the panel surface temperature is maintained at a lower level, thereby reducing the efficiency degradation term.

2.2. Heat dissipated by the PV module

In a water-cooling system, heat exchange between the PV panel surface and the mixed water layer plays a key role in maintaining the panel temperature at an optimal level. Water is distributed directly onto the panel surface and acts as a heat-transfer medium, absorbing excess heat generated during operation. This process involves heat transfer at the contact interface between the panel and water and the thermal energy accumulation within the water flow. At the interface, heat from the PV panel is transferred to water due to the temperature difference between the two media, according to the heat-transfer equation:

$$Q = \alpha \times A \times (T_{panel} - T_{water}) \text{ (W)} \quad (3)$$

where: Q_{heat}: cooling heat removal rate (W);

α: heat-transfer coefficient;

T_{panel}: PV panel surface temperature (°C);

T_{water}: cooling-water temperature (°C).

2.3. PV module power output

High operating temperature is one of the primary factors that degrades the performance and electrical energy production of PV panels, particularly under strong irradiance in tropical regions. Applying water-based cooling is an active and effective method to control the surface temperature of photovoltaic cells, thereby improving the generated power and the total electrical output of the system. The output power after water cooling is determined as follows [8]:

$$P_{effective} = G_T \times \tau_{PV} \times \eta_{ref} \times A \times [1 - \gamma_{ref} \times (T_C - 25)] \text{ (W)} \quad (4)$$

where:

G_T: solar irradiance intensity (W/m^2);

τ_{PV}: transmittance of the PV protective glass layer (%);

η_{ref}: efficiency at the reference condition T_{ref} = 25°C, and GT = 1kW/m^2;

A: PV panel surface area (m^2);

γ_{ref}: power–temperature coefficient (%/K);

T_C: operating temperature of the PV panel (°C).

3. Experimental study

3.1. Experimental setup

Figure 1 below illustrates the experimental setup for this study involving various testing scenarios [9]. In this setup, the PV module was tested under three different cooling methods: natural convection air cooling, forced convection cold air cooling, and the utilization of condensate water from an air conditioner's evaporator - the latter being the primary method presented in this paper.

The volume of condensate from the evaporator is typically small and fluctuates based on operating conditions, making it difficult to meet the continuous cooling demands of the PV module. This study proposes an approach that mixes the condensate source with domestic water to ensure an adequate coolant supply, thereby enabling continuous operation and sustained cooling efficiency. Furthermore, the presence of ions in domestic water enhances thermal conductivity, while the integration of these sources promotes resource recycling, minimizes water waste, and provides environmental protection, ensuring stable system performance under all conditions.

As illustrated in Figure 1, the PV module is tilted at an angle of 30° from the horizontal. The cooling medium is water, which undergoes forced convection as it contacts the external back surface of the panel. The blended water, maintained at a temperature between 17.5°C and 22.5°C, is pumped through conduits to a misting system installed beneath the PV module, with an adjustable flow rate ranging from 3 to 5 L/min. The nozzles generate a fine mist or small droplets to cool the module surface. Upon contact with the panel's surface, the mist evaporates, absorbing heat from the cells and effectively reducing the surface temperature. After the misting and heat absorption process, the water flows downward and undergoes natural cooling via a zigzag structured plate before being recovered into a storage tank, forming a closed-loop circulation system.

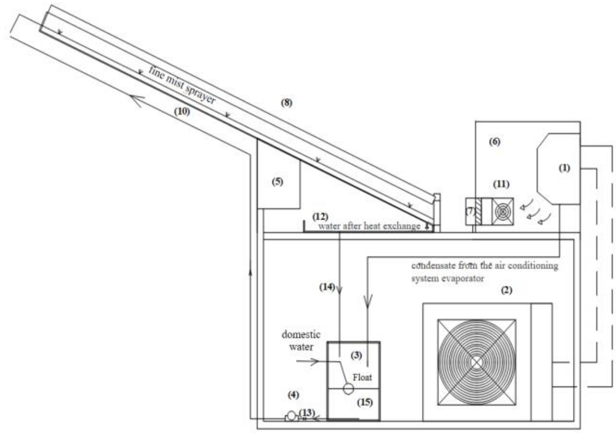

Figure 1. *Experimental model of supplying mixed water between condensed water from the evaporator and domestic water to cool the PV*

(1) Evaporator, (2) Condenser, (3) Mixing water tank, (4) Misting pump, (5) Control cabinet, (6) Cooling air box, (7) Flow regulator, (8) Solar panel, (9) Flexible joint, (10) Cold air guide box to cool the PV, (11) Fan to adjust speed and air flow according to experimental index, (12) Water collection tray after cooling the PV, (13) Water flow pressure regulator valve, (14) Mixing water temperature sensor, (15) Water temperature sensor after cooling

3.2. Experimental design

The research team utilized Minitab software to establish an experimental design based on the Taguchi method in the project [9]. The design matrix consists of 27 experimental trials with three input variables: coolant flow rate (L/min), inlet water temperature (°C), and solar irradiance intensity (W/m^2). The three corresponding output variables include: heat dissipation (W), power output (W), and efficiency (%). In this paper, the analysis is specifically focused on the influence of the cooling water temperature on the three output parameters, with the water flow rate varying from 3 to 5 L/min and solar irradiance ranging from 800 to 1000 W/m^2.

3.3. Measurement method

The The experimental setup was installed on a building rooftop in Ho Chi Minh City, characterized by an open and unobstructed environment. Data collection was conducted from October to November 2024, with measurements taken daily between 9:00 AM and 3:00 PM. This period was selected to coincide with peak solar irradiance (recorded between 800 and 1000 W/m²), thereby avoiding the influence of weak light or low incidence angles and ensuring an accurate evaluation of the cooling system's impact on PV performance under real-world conditions.

Temperature sensors were positioned at specific nodes on the PV panel and within the cooling water, as illustrated in Figure 2. Data were logged at 5-minute intervals using the equipment listed in Table 1 to ensure a high measurement density capable of capturing instantaneous fluctuations caused by weather changes. Experiments were carried out continuously over several days to eliminate random errors from atmospheric conditions and to assess the system's stability and repeatability. During the measurement process, parameters such as solar irradiance, current, voltage, ambient temperature, and panel surface condition were recorded simultaneously to ensure high data reliability and a comprehensive reflection of all influencing factors.

Table 1. *Specifications of instruments used in the experiments*

No.	Instrument	Quantity	Operating range / Key specifications
1	Mist nozzle	20	Pressure: 35 kg/cm^2 (≈495 psi); Dimensions: 24.5 × 9.4 × 9.4 mm
2	Smart Pumps KJ-15 mist pump (with 24V supply)	1	Spray pressure: 5 kg/cm^2; Flow rate: 5 L/min
3	LONGi Solar 450W photovoltaic panel	1	Monocrystalline type; Dimensions: 1038 × 2094 × 35 mm; Weight: 27.5 kg
4	NTC temperature sensor	4	Measuring range: -50 ^{0}C → 110^{0}C
5	Extech HD350 temperature, pressure and air flow meter	1	Pressure accuracy: ±0.3% FS; Air velocity: 1–80 m/s; Flow accuracy: ±3%
6	JUANJUAN GM816 air temperature and velocity meter	1	Range: 0–30 m/s; Accuracy: ±2 ^{0}C
7	Current and voltage display unit	1	Range: 0–100 VDC; Operating temperature: -10→65^{0}C; Error: ±0.1%
8	TENMARS TM-206 solar power meter	1	Range: 0–2000 W/m²; Resolution: 0.1 W/m²; Accuracy: ±5%
9	VC326L+ digital clamp multimeter	1	DC voltage: 600V ± (0.8%+3dgt); AC voltage: 450V ± (1.2%+5dgt)

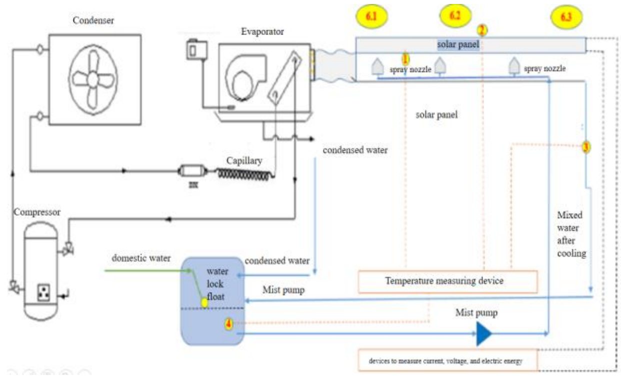

Figure 2. *Schematic diagram of equipment layout used for experimental cooling of solar panels using mixed water*

The integration of the surface cooling system - utilizing a blended-water misting method - combined with a strategically designed sensor network for thermal and electrical data acquisition, facilitated a precise evaluation of the cooling effect on the photovoltaic (PV) system's energy conversion efficiency. The collected data serves as a critical foundation for analyzing, comparing, and proposing solutions to enhance solar energy harvesting efficiency under real-world operating conditions. Furthermore, these measures contribute significantly to extending the operational lifespan of the PV modules.

As illustrated in Figure 2, solar irradiance was measured using the TENMARS TM-206 meter. Condensate water was mixed with regular water to cool the PV panel surface by spraying the mixed water (via the Smart Pumps KJ-15 pump) onto the surface. The temperature measurement system included four NTC sensors: two sensors measured water temperature in the mixed-water tank before cooling (position 4) and after cooling (position 3), and two sensors measured temperatures on the upper surface (position 2) and lower surface (position 1) of the PV panel. Current, voltage, and energy consumption were also recorded. Under solar irradiance, the PV module generates electrical quantities, and the measurement devices captured the energy conversion parameters from thermal energy to electrical energy.

4. Results and discussion

Based on the experimental results in Figure 3, under the best irradiance condition G = 1000 W/m², when the cooling-water temperature increased from 17.5°C to 22.5°C, the system efficiency decreased from approximately 19.8% to 18.7%, while the obtained power decreased from about 430 W to around 415 W. The power reduction was approximately 15 W, corresponding to nearly 3.5%. The simultaneous downward trend in both efficiency and power indicates that a higher cooling-water temperature reduces the heat dissipation capability of the system, leading to an increase in the operating temperature of the collector and increased convective–radiative heat losses. This result confirms the decisive role of cooling-water temperature in maintaining energy conversion performance, particularly in the low-temperature range of 17.5–19.5°C, where the system achieves clearly higher efficiency and power.

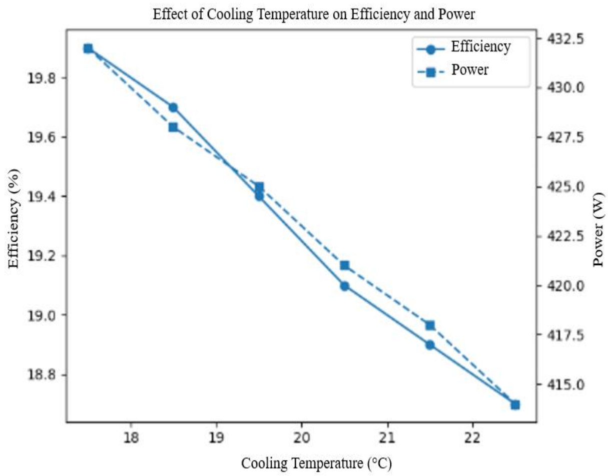

Figure 3*. Relationship of PV efficiency and power output as a function of cooling water temperature.*

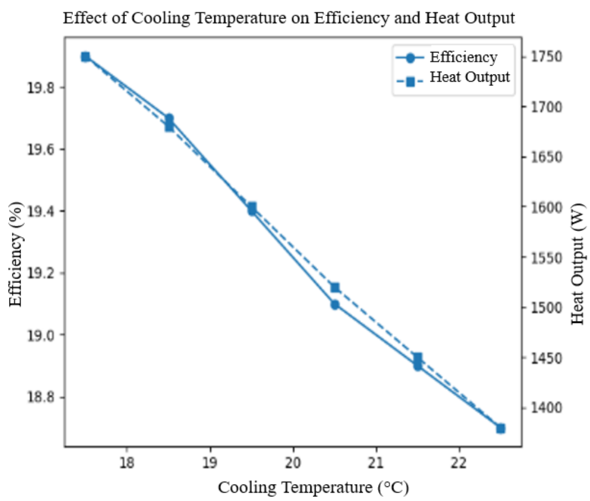

Figure 4*. Relationship of PV efficiency and heat rejection as a function of cooling water temperature.*

Figure 4 illustrates that the cooling water temperature has a direct and significant impact on both the efficiency and the heat dissipation of the system, under a spray flow rate of 5 L/min and a solar irradiance intensity of G = 1000 W/m². When the cooling-water temperature increased from 17.5 °C to 22.5 °C, both efficiency and heat transfer rate decreased with an approximately linear trend. Specifically, efficiency decreased from about 19.8% to 18.7%, corresponding to a reduction of approximately 1.1 percentage points. In parallel, the obtained heat transfer rate decreased from roughly 1750 W to about 1400 W, indicating that the system's heat collection and transfer capability decreased substantially as the cooling-medium temperature increased. The primary reason is the reduction in the temperature difference between the absorbing surface and the cooling medium, which reduces the heat transfer rate and results in a higher operating temperature of the absorbing surface. Consequently, heat losses to the environment increase, reducing the useful energy obtained and leading to a decrease in the overall system efficiency.

The similarity in trends between the efficiency curve and the heat transfer curve in the figure indicates that the cooling-water temperature is a strongly governing parameter for system operating performance. In the lower cooling-temperature range (17.5–19.5 °C), the system achieves high efficiency (≈ 19.6–19.8%) and high heat transfer rate (>1600 W). When the cooling temperature increases above 21.5 °C, both efficiency and heat transfer rate decrease noticeably, thereby reducing energy utilization effectiveness.

The temperature gradient between the PV panel and the cooling medium (ΔT) plays a pivotal role in the heat dissipation process. As the temperature of the cooling medium increases, the ΔT decreases, leading to a reduction in the convective heat transfer coefficient, which in turn diminishes cooling effectiveness. This causes the panel temperature to rise further, creating a detrimental feedback loop regarding efficiency. Consequently, the overall efficiency depends not only on the photovoltaic cells themselves but also on the heat dissipation conditions of the surrounding environment.

In summary, effective thermal management helps maintain the PV module's operating temperature near its optimal level, thereby mitigating efficiency degradation caused by high temperatures. This leads to an increase in power output and energy yield, directly enhancing revenue or reducing grid electricity costs. Furthermore, a stable operating temperature contributes to limiting the degradation process of the panels and reducing the frequency of maintenance and replacement, resulting in long-term operational cost savings.

5. Conclusions

The theoretical and experimental results of enhancing PV module efficiency by utilizing a mixture of condensate from the air conditioning evaporator and domestic water are in full agreement with the theoretical framework regarding the temperature dependence of PV efficiency and power output. As the operating temperature of the panel increases - particularly when exceeding the Standard Test Condition (STC) threshold of 25°C-the open-circuit voltage (V_{oc}) of the photovoltaic cells drops rapidly, while the current increase remains negligible, leading to a degradation in overall power output.

The active cooling method using blended water, specifically incorporating recovered condensate from air conditioning units, demonstrates a pronounced effect on enhancing performance and operational stability of PV modules under hot and humid tropical conditions. These findings prove that utilizing recovered condensate for cooling helps maintain the panel temperature at a low level, thereby improving energy conversion efficiency. Within the cooling temperature range of 17.5°C to 22.5°C, the PV efficiency fluctuates between 19.5% and 20.08%. This improvement is attributed to the fact that the PV backsheet is significantly cooler (averaging about 15°C lower) compared to natural convection, which mitigates thermal degradation and maintains the power output near its theoretical value.

This solution offers not only technical advantages but also significant economic and environmental value. By reclaiming low-temperature condensate-a readily available resource that is typically discarded-the system reduces investment costs, conserves water resources, and enhances the overall efficiency of the air conditioning system. Furthermore, the cooling process contributes to minimizing energy losses and mitigating indirect CO_2 emissions from fossil fuel sources, advancing the development of clean, efficient, and sustainable energy in modern buildings.

The comprehensive dataset obtained allows for the development of simulation models to characterize PV module efficiency as a function of variables such as ambient temperature, operating temperature, solar irradiance, and cooling conditions. Both linear and non-linear regression models can be derived from these data to facilitate performance prediction and system optimization under real-world operating conditions. Additionally, future research should focus on a techno-economic evaluation of hybrid active cooling solutions - combining air and water - while assessing the long-term impact of the cooling process on material durability and system lifespan. The development of real-time performance simulation models is essential to support the design, control, and operational optimization of these systems in practical applications.

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