Performance of Autonomous Temperature Controlled Photovoltaic Modules with Water Film

Jinbao Li*, Zeyi Xi and Sen Wu
College of Mechanical and Electrical Engineering, Hohai University, Changzhou, China

*Corresponding author e-mail: 1661310217@hhu.edu.cn

Abstract. In order to reduce the surface temperature of solar cells and reduce the surface dust and improve the power generation efficiency of PV modules, this paper introduces a cooling device for PV modules based on temperature self-regulation, including PV power generation, circulating water and temperature control system. The theoretical heat transfer model of the experimental device during operation is established. Set the temperature control interval of the temperature control system, and compare the test with the same type of panel with the no-surface film flowing at the same inclination angle. The research showed that when the average ambient temperature is 21.61 °C, the average temperature of the panel without water film cooling is about 35.37 °C, and the average temperature of the panel with the water film cooling is about 25.53 °C, which achieves the purpose of cooling and temperature control. At the same time, the output power of the water film cooling panel is relatively increased by about 13.57%. In summary, the water film cooling device in this paper can effectively reduce and stabilize the temperature of the PV module, reduce surface dust and increase its output power.

1. Introduction
The power generation efficiency of traditional solar cells is affected by surface temperature and dust. Reducing the surface temperature of solar cells and reducing the surface dust can improve the power generation efficiency of the battery. Research work by researchers shows that dust removal and cooling have important implications for photovoltaic power generation.

Regarding dust removal, Difei Fan et al [1] summarized several self-cleaning methods for solar panels, such as natural dust removal, mechanical dust removal, electric curtain dust removal and nano self-cleaning film dust removal. Xiaoyan Liu et al [2] designed an intelligent dust removal device that can be attached to the surface of the component for automatic walking. It is controlled by a programmable controller and uses dry rubbing and spray to remove dust. It has been proved by experiments that the device can make solar panels. Power generation increased by 4%. Zhang Junbin et al [3] designed a smart dust collector, which uses a screw rod as the transmission mechanism. The cleaning brush consists of a brush and a roller brush.

Regarding cooling, many scholars have done a lot of research on water-cooling cooling in recent years. Abdolzadeh et al [4] increased system efficiency by spraying water on the back of the solar panel. Jianbo Chen et al [5] analyzed and compared the cooling methods of copper tube water cooling and surface water cooling. The results show that the two methods increase the battery conversion efficiency by 0.3% and 3% respectively. Bahaidarah [6] pointed out that the temperature non-uniformity on the surface of the PV panel has a great influence on the overall performance of the PV system, which will directly increase the battery resistance, resulting in a decrease in the output power.
of the system; it cools the panel by means of jet cooling [7], performance evaluation of PV panels under different water flow conditions. Experiments show that the power generation efficiency of jet-cooled panels is significantly higher than that of non-jet cooling; it is cooled down with traditional rectangular channel heat exchangers. Comparing the panels, experiments have shown that when the battery temperature in operation is as high as 83 °C, the rectangular channel heat exchanger reduces the temperature to 47.4 °C, while the jet cooling reduces the temperature to 37 °C, and further explores the different jet modes of water on cooling. Zhang et al [8] analyzed and compared the advantages and disadvantages of natural circulation cooling, forced circulation cooling and other techniques, and proposed a non-power cooling technology, which attaches the cooling material with moisture absorption function to the back of the photovoltaic panel and absorbs it by evaporation. The heat of the photovoltaic panel to achieve the purpose of cooling. Changjun Shen et al [9] used evaporative cooling to cool the surface of the photovoltaic panel, effectively increasing the amount of electricity generated. Rabie et al [10] proposed the use of phase change materials for intensive cooling, but there is a problem of low thermal conductivity of phase change materials. Simpson et al [11] pointed out that the operating temperature of photovoltaic panels in outdoor environments is usually 25 °C higher than the ambient temperature, and the output power may be less than 70% of the rated power; it uses a desiccant to cool the photovoltaic modules, and the desiccant absorbs air at night. Water that absorbs excess heat during the day. Chatterj et al [12] compared the temperature of components in two side-by-side PV arrays without and with a fan cooling system.

It can be seen that cooling and dust removal are of great importance to solar panels, and the cooling of water film can achieve two purposes at the same time. In this paper, a water-film cooling device for photovoltaic modules based on temperature self-regulation is proposed. By forming a flowing water film on the surface of the solar cell, the purpose of cooling and dust removal is achieved, and according to the temperature of the back of the panel, the self-control device is started and stopped by the MCU. The temperature of the component is maintained within the set temperature range, and the application characteristics of the device are explored through comparative experiments.

2. Theoretical heat transfer model for photovoltaic module water film cooling device

The front panel of the PV module water film cooling device belongs to the forced convection heat transfer of the fluid-extracting plate [13]. The back panel belongs to the natural convection heat transfer of the air, in addition to the radiation heat transfer of the PV module to the surrounding environment.

2.1. Overall heat transfer model

![Heat transfer model of photovoltaic module with water film cooling](image)

For the PV module as a whole, there is an energy conservation equation as shown in equation (1).

\[
\frac{dT}{dt} = \frac{E_{s} - Q_{f} - Q_{c} - Q_{r} - P_{out}}{Cm}
\]  

In the equation, \(E_{s}\) - Solar radiation received by photovoltaic panels, \(W\); \(Q_{f}\) - Heat of forced convection on the front side of photovoltaic panels, \(W\); \(Q_{c}\) - Heat of natural convective on the back of photovoltaic panels, \(W\); \(Q_{r}\) - Radiation heat of photovoltaic panels to the environment, \(W\); \(P_{out}\) -
Photovoltaic panel output power, $W$; $T$ - Panel temperature, take the temperature of the back of the photovoltaic panel, $K$; $C$ - Specific heat capacity of photovoltaic panels, $J/(kg\cdot K)$; $m$ - The quality of a single panel, $kg$.

2.1.1. The amount of solar radiation received by the PV panel

The sunlight is irradiated on the photovoltaic panel through the surface water film, and there is reflection and transmission of light. The schematic diagram of the propagation path of the light is shown in Fig. 2

\[ E_s = A(1 - \rho) I_s \tau \]  

(2)

In the equation, $A$ - Area of a single photovoltaic panel, $m^2$; $\rho$ - Reflectivity of water to solar radiation; $\tau$ - Water transmission to solar radiation; $I_s$ - The amount of solar radiation that strikes the surface of a photovoltaic panel, $W/m^2$.

2.1.2. Heat of forced convection on the front side of PV panels

The front side of the PV panel is the forced convection heat transfer of the fluid-extracting plate. The Reynolds number $Re$ is calculated according to the experimental conditions. The boundary layer on the plate is composed of the laminar flow segment and the turbulent flow segment. The calculation is carried out by the formula [14] to obtain the water and the battery. The calculation equation for the convective heat transfer on the front side of the plate is shown in equations (3)~(5)[13].

\[ Q_f = Ah_f (T - T_{water}) \]  

(3)

\[ h_f = \left( \frac{\lambda_i}{Nu_{i}} \right) / l \]  

(4)

\[ Nu_{i} = 0.037 \left( Re^{0.85} - 871 \right) Pr^{1/3} \]  

(5)

In the equations, $h_f$ - Forced convection heat transfer coefficient on the front side of photovoltaic panel, $W/(m^2\cdot K)$; $T_{water}$ - Average temperature of water, $^\circ C$; $\lambda_i$ - Thermal conductivity of water, $W/(m\cdot K)$; $Nu_i$ - Nusselt number in the heat transfer state of photovoltaic panel; $Re$ - Reynolds number; $Pr$ - Prandtl number.

2.1.3. Heat of natural convective on the back side of PV panels

The back of the solar panel is the natural convection heat transfer of the air, and it is the natural convection heat transfer in the finite space. Therefore, the convective heat transfer power is calculated by the inclined finite space interlayer calculation model. The equation is as shown in equations 6)~(9)[14 ].

\[ Q_c = Ah_c (T - T_{air}) \]  

(6)

\[ h_c = \left( \frac{\lambda_i}{Nu_{c}} \right) / l \]  

(7)

\[ Nu_{c} = 1 + 1.44 \left( 1 - \frac{1708}{Ra_{\delta} \cos \theta} \right) \left[ 1 - \frac{1708(\sin 1.8 \theta)^{1.6}}{Ra_{\delta} \cos \theta} \right] + \left[ \frac{Ra_{\delta} \cos \theta}{5830} \right]^{-\frac{1}{3}} - 1 \]  

(8)
In the equations, \( h_2 \) - Natural convection heat transfer coefficient on the back of photovoltaic panels, \( W/(m^2 \cdot K) \); \( T_{air} \) - Ambient temperature, °C; \( Nu_2 \) - Nusselt number in the heat transfer state of the photovoltaic panels; \( \lambda_1 \) - Thermal conductivity of air, \( W/(m \cdot K) \); \( Ra_\delta \) - Rayleigh number; \( \beta \) - Installation angle of photovoltaic panels; \( g \) - Local gravity acceleration, \( m^2/s \); \( \delta \) - Sandwich thickness, \( m \); \( \nu \) - Kinematic viscosity, \( m^2/s \); \( a \) - Thermal diffusivity, \( m^2/s \).

### 2.1.4. Radiation heat of photovoltaic panels to the environment

The amount of heat radiated by the photovoltaic panel to the environment is equal to its total radiant heat minus the heat radiated to the sky and the ground, as shown in equations (10) to (12) [13].

\[
Q_r = A\sigma_0 \left( e_s T^4 - X_{as} e_{as} T_{sky}^4 - X_{g'} e_{g'} T_{g'}^4 \right)
\]

\[
X_{as} = \frac{1 - \cos \beta}{2}
\]

\[
X_{g'} = \frac{1 + \cos \beta}{2}
\]

In the equations, \( \sigma_0 \) - Black body radiation constant, \( \sigma_0 = 5.67 \times 10^{-8} \); \( e_s \) - Photovoltaic panel radiance; \( X_{sky} \) - The angle coefficient of the back of the photovoltaic panel to the sky; \( e_{sky} \) - Sky radiance; \( T_{sky} \) - Sky temperature, \( K \); \( X_{gr} \) - Angle coefficient of the back side of the photovoltaic panel to the ground; \( e_{gr} \) - Ground radiance; \( T_{gr} \) - Ground temperature, \( K \).

### 2.2. PV module output power model

The fill factor model constant [15], the output power of the photovoltaic module is shown by equation (13).

\[
P_{out} = C_{FF} \frac{I_s \ln (CI_s)}{T}
\]

In the equation, \( C_{FF} \) - Fill factor model constant, \( C_{FF} = 1.22 \cdot K \cdot m^2 \); \( C \) - Constant, \( C = 10^6 \cdot m^2/W \).

### 2.3. PV module operating temperature calculation

Substituting equations (2) to (13) into equation (1), and calculating the temperature of the PV module \( T \), as shown in equation (14).

\[
\begin{align*}
C_m \frac{dT}{dt} &= A(1 - \rho) I_s \tau - A h_1(T - T_{air}) - A h_1(T - T_{as}) - A\sigma \left( e_s T^4 - X_{as} e_{as} T_{sky}^4 - X_{g'} e_{g'} T_{g'}^4 \right) - C_{FF} \frac{I_s \ln (CI_s)}{T} \\
&\quad - \rho I_s \tau - A h_1(T - T_{air}) - A h_1(T - T_{as})
\end{align*}
\]

### 3. Design of water film cooling device for photovoltaic modules

#### 3.1. Overall system design

The structure of the water film cooling device is composed of a photovoltaic power generation part, a circulating water part and a temperature control part, and the block diagram is shown in Fig.3. Among them, the photovoltaic power generation part is a solar photovoltaic panel with a certain inclination angle, and the light energy is converted into electric energy by the photovoltaic effect. The circulating water part is composed of a water storage tank, a direct current water pump, a water pipe and a nozzle, and a water film is formed on the photovoltaic plate by circulating water. The temperature control part is composed of a temperature sensor, a single chip microcomputer and a relay, and controls the start/stop of the circulating water system based on the temperature of the back side of the photovoltaic panel.
3.2. Temperature control system design
According to the design scheme, the device can self-monitor the temperature of the back surface of the photovoltaic panel in real time, and control the opening and closing of the water film cooling device according to the temperature. Detailed description of the preferred embodiments as shown in Fig. 4, the temperature sensor model is DS18B20, and the single-chip model is AT89S52. The temperature sensor detects the temperature $T$ of the back surface of the photovoltaic panel and transmits it to the single-chip microcomputer for processing, and the preset temperature values $T_1$ and $T_2$ ($T_1 > T_2$). For comparison, when $T > T_1$, the relay is closed, the pump works to form a water film to cool the PV module; when $T < T_2$, the relay is disconnected and the pump stops working. Thereby achieving the independent temperature control function of the photovoltaic panel.

3.3. System overall hardware structure design
According to the design scheme, the water film cooling device is built on the top of the photovoltaic panel, thereby forming a water film on the surface of the photovoltaic panel, reducing the temperature of the photovoltaic module, reducing the dust on the surface, thereby improving the power generation
efficiency of the photovoltaic module. At the same time, the temperature control system monitors the temperature of the photovoltaic module in real time, stabilizes the temperature of the photovoltaic module in a certain temperature range, realizes independent temperature control, and avoids the uninterrupted work of the water circulation system. The overall hardware structure of the system is shown in Fig. 5.

![Figure 5. Hardware structure diagram of the whole system](image)

4. Experimental design and results analysis

4.1. Experimental system design

In this experiment, a comparative experimental study method was adopted. In order to ensure the consistency of external conditions as much as possible, a solar simulator was used instead of sunlight to perform experiments in an indoor environment. This can not only ensure the constant change of irradiance, but also reduce the influence of various factors such as external airflow and ambient temperature on the experiment, and ensure that there is only one variable of water film cooling device in the comparison experiment.

According to the overall hardware structure diagram of the system, the experimental platform is built. The experimental device is shown in Fig. 6. The temperature value T1 in the temperature control system was set to 27 °C, and T2 was set to 24 °C, as shown in Fig. 7. The experimental data was recorded using equipment such as volt-ampere characteristic tester and irradiance meter, and 50 sets of data were obtained from 10:00 am to 16:00 pm.

![Figure 6. Physical diagram of the experimental apparatus](image)
4.2. Analysis of results

4.2.1. Temperature result analysis
Run the experimental device and test the relevant data. First, observe the actual cooling effect of the device on the photovoltaic panel. Figure 8 shows the ambient temperature and average backsheet temperature of a PV panel with a water film cooling device and a fixed PV panel with a certain irradiation intensity.

![Figure 8. Diagram of temperature changes](image)

As can be seen from Figure 8, the water film cooling device can significantly reduce the temperature of the PV panel. The average temperature of a fixed-angle PV panel without a water film cooling device is about 35.37 °C, and the maximum temperature can reach above 42 °C. The average temperature of the PV panel with the water film cooling device is about 25.53 °C, and the average temperature is about 10 °C. At the same time, the ambient temperature is about 21.61 °C. On the one hand, the designed water film device can really reduce the temperature of the PV panel. On the other hand, the temperature of the PV panel fluctuates stably at 25 °C, which is consistent with the temperature range set by the temperature control system (T1 is 24 °C, T2 is 27 °C), the average...
temperature of the PV panel is stable within the temperature range, achieving independent temperature control of the photovoltaic module. In summary, the water film cooling device is effective for reducing the temperature of the PV panel, and can also set the temperature range of the temperature control system to stabilize the temperature of the PV panel.

4.2.2. Performance analysis

The performance of the PV panel was analyzed under the same conditions as above. Fig. 9, Fig. 10 and Fig. 11 respectively show the comparison of the open circuit voltage, short circuit current and power generation of the PV panel with the water film Cooling device and the PV panel with the fixed angle.

![Figure 9. Diagram of open circuit voltage variation](image)

Figure 9 is a comparison of the open circuit voltage of the PV panel. The open-circuit voltage of the fixed-angle PV panel without the water film cooling device is about 34.95V, and the open circuit voltage of the PV panel with the water film cooling device is about 36.75V, which is about 5.15% higher than that of the previous year. That is, the PV board open circuit voltage with the water film cooling device increased slightly, and the PV panel with a fixed angle of inclination increased by about 5.15%.

![Figure 10. Diagram of short circuit current variation](image)
Figure 10 is a comparison of the short-circuit current of the PV panel. The short-circuit current of the fixed-angle PV panel without the water film cooling device is about 6.23A, and the short-circuit current of the PV plate with the water film cooling device is about 6.57A, which is about 5.45% higher than that of the previous year. That is, the short-circuit current of the PV panel with the water film cooling device increased slightly, and the PV panel with the fixed inclination angle increased by about 5.45%.

![Diagram of generation power variation](image)

Figure 11. Diagram of generation power variation

Output power is the most important reference for the performance of PV modules. Figure 11 shows a comparison of the operating power of the PV panel. The output power of the fixed-angle PV panel without the water film cooling device is about 162.42W, and the output power of the PV panel with the water film cooling device is about 184.46W, which is about 13.57% higher than that of the previous year. That is, the output of the PV panel with the water film cooling device is about 13.57% higher than that of the PV panel with the fixed inclination angle, and the effect is obvious.

The experimental results show that the water film cooling device has obvious improvement on the performance of the PV panel, including open circuit voltage, short circuit current and output power. Therefore, we can use this water film cooling device based on the back surface temperature of the photovoltaic panel to realize the performance of the PV panel. Improvement.

5. Conclusion

In this paper, a water-film cooling device for PV modules that can achieve temperature self-regulation is proposed, and the establishment and experimental research of related heat transfer models are carried out. The above results indicate that:

1) The water film cooling device can reduce the temperature of the photovoltaic module, and the temperature of the photovoltaic module can be stabilized within the set temperature range by the temperature control system composed of the single chip microcomputer.

2) The water film cooling device has a practical effect on the performance improvement of the photovoltaic module. When the ambient temperature is 21.61 °C, the power generation efficiency of the single photovoltaic panel is increased by about 13.57%.

The device solves the problem of dust removal and temperature reduction of the photovoltaic component, realizes the independent temperature control of the photovoltaic component, and has practical application value. At the same time, this method provides an important basis for the future research on the performance improvement of photovoltaic modules.
Acknowledgements
This work was financially supported by the Jiangsu University Innovation and Entrepreneurship Training Project of China (NO. 201810294075X).

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