Mathematical Model Establishment and In-situ Experimental Verification about the Effects of Meteorological Environmental Factors on the Temperature of Photovoltaic Module

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Abstract: The temperature of photovoltaic (PV) module is an important factor to determine its power generation performance, and the temperature rise will cause the reduction of photoelectric conversion efficiency, which is directly related to the meteorological environmental factors. In this study, based on the heat transfer model of PV module, the mathematical model representing relationship between PV module temperature and ambient temperature, solar radiation intensity, and wind speed was established by thermal equilibrium analysis. Furthermore, the model was validated based on the measured data of the experimental platform.

1. Introduction
Solar photovoltaic (PV) power generation has long been seen as a clean and renewable energy technology, which has been highly valued and widely used by many countries. After years of development, the technology of solar PV power generation has become relatively mature and promising, but for now, the efficiency of PV modules is still relatively low, in particular, the efficiency of commercial PV modules is generally less than 20%. The PV conversion efficiency of solar cells is related to the temperature of PV modules. Direct exposure of the surface of PV modules to the solar radiation leads to the increase in the sensitivity of the working conditions of the PV module toward temperature. Therefore, temperature is an important factor that affects the module efficiency and generated electric powers of PV modules. Research results show that the photoelectric conversion efficiency of solar cells decreases linearly with the increase of PV module temperature [1]. Generally, the equipment manufacturer provides the temperature coefficient of PV modules. Temperature of PV module depends upon many meteorological environmental factors including ambient temperature, solar radiation intensity, wind speed, and wind direction and so on [2]. In order to improve the efficiency of PV modules and make full use of the solar energy, investigation of the impact of environmental factors on the temperature of PV modules is highly desirable.

In the PV module power generation process, only a small part of the energy in the absorption process of solar radiation is turned into electrical energy, while most of the energy is turned into heat
which is passed again to the environment through radiation and convection; therefore, the temperature of the PV module is generally higher than the ambient temperature. The energy absorbed by PV modules is related to the solar radiation intensity. The convective heat dissipation and radiant heat transfer of PV modules are affected by ambient temperature, wind speed, and wind direction. Thus the change in solar radiation intensity, ambient temperature, and wind speed and direction affect the PV module temperature, which in turn determines the photoelectric conversion efficiency that ultimately affects the power generation performance of PV modules. With respect to the study on the influence of meteorological environmental factors on the performance of PV modules, Kaldellis et al. established a test platform in southern Greece, and the monitored one year’s data indicated that the temperature difference between PV module temperature and ambient air temperature decreased with the increase of wind speed, when the other conditions remained the same, i.e., the greater the wind speed, the greater the output power of PV modules [3]. Gokmen et al. conducted experimental study to predict the output performance of PV modules, and the results indicated that the output power could be more accurately predicted by taking into account the effects of wind speed, in particular, in high altitude and windy areas [4]. Koehl et al. found that the wind speed of 10 m s$^{-1}$ could reduce the temperature of PV modules by 15 to 20 °C when the solar radiation intensity was 1000 W m$^{-2}$ [5]. Schwingshackl et al. studied the cooling effect of wind speed on the temperature of PV modules and established a mathematical model for obtaining the relationship between the module temperature and wind speed [6]. Xu et al. proposed relationship between the temperature of PV modules and the ambient temperature and radiation intensity by statistical analysis of test data, and the result showed that the temperature of PV modules was proportional to both the ambient temperature and radiation intensity, and the influence of wind speed could be neglected [7]. Sheng et al. established a thermoelectric coupling model of PV modules and found that the temperature of PV modules decreased with the decrease of the ambient temperature; moreover, the extent of variation of the module temperature was basically equal to that of the ambient temperature [8]. As can be seen above, the investigations on the influence of meteorological environmental factors on the temperature of PV module were conducted only in the recent years, the number of systematic and deep-going investigations in the field of photovoltaic power generation is quite few.

Based on the basic theory of PV power generation, in this study the mathematical model representing relationship between PV module temperature and solar radiation intensity, ambient temperature, and wind speed was established by thermal equilibrium analysis. Furthermore, the model was experimentally validated with the established experimental platform in Xi’an.

2. Establishment of mathematical model

2.1. Thermal equilibrium of photovoltaic modules

When the surface of solar cells is exposed to sunlight, they absorb the light, which leads to the photoelectric effect. Part of the energy is converted into electrical energy output, while the other part of the energy is converted into heat and then passed to the environment through heat radiation and heat convection, and there is yet another part of the energy which is being stored. According to the law of conservation of energy, the thermal equilibrium equation of PV modules can be expressed as follows:

$$Q_{\text{tot}} = Q_{\text{out}} + Q_{\text{loss}} + Q_{\text{sto}}$$  \hspace{1cm} (1)

where, $Q_{\text{tot}}$ is solar radiation energy absorbed by PV modules (J); $Q_{\text{out}}$ is output energy by PV modules (J); $Q_{\text{loss}}$ is total energy loss of PV modules (J); and $Q_{\text{sto}}$ is internal stored energy (J).

The solar radiation energy absorbed by PV modules is expressed as follows:

$$Q_{\text{tot}} = \tau I_T \phi A t$$  \hspace{1cm} (2)

where, $\tau$ is the transmittance of the front glass panel of PV modules; $\phi$ is the absorption rate of solar cells for solar radiation; $I_T$ is the solar radiation intensity on the surface of PV modules (W m$^{-2}$); $A$ is PV module surface area (m$^2$); and $t$ is time (s).

The output energy by PV modules is:
where, $\eta$ represents the efficiency of PV modules and it is represented as follows:

$$\eta = \eta_{\text{ref}} [1 - \beta_{\text{ref}} (T_{\text{PV}} - T_{\text{ref}})]$$

where, $\eta_{\text{ref}}$ is the efficiency of PV modules under standard test conditions; $\beta_{\text{ref}}$ represents temperature coefficient of PV modules; $T_{\text{PV}}$ is the operating temperature of PV modules ($^\circ$C); and $T_{\text{ref}}$ corresponds to the operating temperature under standard test conditions ($^\circ$C).

The total energy loss of the modules $Q_{\text{loss}}$ corresponds to the energy dissipated by thermal convection and radiation into the environment, including the energy loss from the front panel of PV modules and the energy loss from the back panel, expressed as follows:

$$Q_{\text{loss}} = U_{L, f} \times (T_{\text{PV}} - T_a) A dt + U_{L, b} \times (T_{\text{PV}} - T_a) A dt$$

where, $T_a$ is ambient temperature ($^\circ$C); $U_{L, f}$ represents heat loss coefficient of the front panel of PV modules (W m$^{-2}$ $^\circ$C$^{-1}$); $U_{L, b}$ is the heat loss coefficient of the back panel of PV modules (W m$^{-2}$ $^\circ$C$^{-1}$).

The heat loss coefficients of the front and back panels of PV modules are expressed as follows:

$$U_{L, f} = h_{c, f} + h_{r, f}$$

$$U_{L, b} = h_{c, b} + h_{r, b}$$

where, $h_{c, f}$ is the convective heat transfer coefficient of the front panel of PV modules (W m$^{-2}$ $^\circ$C$^{-1}$); $h_{r, f}$ represents radiation heat transfer coefficient of the front panel of PV module (W m$^{-2}$ $^\circ$C$^{-1}$); $h_{c, b}$ is the convective heat transfer coefficient of the back panel of PV modules (W m$^{-2}$ $^\circ$C$^{-1}$); and $h_{r, b}$ is radiation heat transfer coefficient of the back panel of PV module (W m$^{-2}$ $^\circ$C$^{-1}$).

The stored energy by PV modules is expressed as follows:

$$Q_{\text{sto}} = C \cdot dT$$

where, $C$ is the total specific heat capacity of PV modules (J $^\circ$C$^{-1}$) and $dT$ is the temperature difference between the PV module before and after the time($^\circ$C).

2.2. Convective heat transfer of photovoltaic modules

2.2.1. Natural convective heat transfer coefficient

The natural convective heat transfer coefficient of the front and back panels of PV modules can be calculated according to the Nusselt criterion number $Nu$. The general expression for the Nusselt criterion is $Nu = h \times L/\lambda$, where $h$ is the convective heat transfer coefficient (W m$^{-2}$ $^\circ$C$^{-1}$); $L$ is the size of the specimen (m); and $\lambda$ is the thermal conductivity (W m$^{-1}$ K$^{-1}$).

The natural convective heat transfer coefficient $h$ for the front and back panels of a PV module with an arbitrary tilt angle can be calculated according to the following equation proposed by Vogt et al. [9].

$$Nu_{\text{natural}} = 0.68 + \frac{0.67 \cdot (Gr \cdot Pr \cdot \sin \beta)^{1/4}}{\left[1 + (0.492/Pr)^{9/16}\right]^{1/4}}$$

where, $Gr$ is Grashof number; $Pr$ is Prandtl number; and $\beta$ is tilt angle of PV modules ($^\circ$).

The calculation equations of $Gr$ and $Pr$ are as follows:

$$Gr = \frac{g \cdot (T_{\text{PV}} - T_a) \alpha L^4}{\nu^2}$$

$$Pr = \frac{\nu}{\alpha}$$

where, $g$ is gravitational acceleration (m s$^{-2}$); $\alpha$ is fluid volume expansion coefficient for ideal gas, $\alpha = 1/T_i$ ($T_i$ is temperature of boundary layer [10], and $T_i = (T_{\text{PV}} + T_a)/2$ (1/°C); $L$ is the specimen size (Equation (13)) (m); $\nu$ represents kinematic viscosity (m$^2$ s$^{-1}$); and $\alpha$ is thermal diffusivity (m$^2$ s$^{-1}$).
2.2.2. Forced convection heat transfer coefficient.

The expression for the estimation of forced convection heat transfer coefficient of the front and back panels of PV modules can be derived based on the theoretical expressions provided by Kendoush [11].

\[
Nu_{\text{forced}} = 0.848 \left[ \cos (90^\circ - \beta) \times V_u \cdot Pr / \nu \right]^{0.5} \times (2 \cdot L)^{0.5}
\]

(12)

where, \( \beta \) is the tilt angle of PV modules (\(^\circ\)) and \( L \) is specimen size (m), which is calculated by using the following Equation (13):

\[
L = 4 \times A / S
\]

(13)

where, \( A \) represents surface area of PV modules (m\(^2\)) and \( S \) represents perimeter of PV modules (m).

2.2.3. Natural convection and forced convection integrated heat transfer coefficient.

Regarding the judgement of flow regime, according to White’s research results [12]: when \( Gr_L << Re_L^2 \), natural convection heat transfer can be ignored, and \( Nu_{\text{all}} = Nu_{\text{forced}} \); when \( Gr_L >> Re_L^2 \), forced convection heat transfer can be ignored, and \( Nu_{\text{all}} = Nu_{\text{natural}} \). However, when the value of \( Gr_L/Re_L^2 \) is between 0.01 and 100, it is necessary to consider the effects of both the natural convection heat transfer and forced convection heat transfer, and the corresponding equation is represented as follows:

\[
Nu_{\text{all}} = Nu_{\text{natural}} \pm Nu_{\text{forced}}
\]

(14)

where, \( Nu_{\text{natural}} \) is Nusselt number of natural convection heat transfer and \( Nu_{\text{forced}} \) is Nusselt number of forced convection heat transfer. The plus and minus signs are determined according to the positive and negative correlation between natural convection and forced convection, respectively. In the case of solar radiation, the temperature of PV modules is higher than the ambient temperature, thus the natural convection always flows upwards along the inclined panel. For the front glass panel, the natural convection and forced convection always reinforce each other; therefore, plus sign should be considered. For the back panel, when the back panel is at the leeward side, the effect is strengthening, and the plus sign is considered. However, when the back panel is at the windward side, the effect is weakening and minus sign should be considered. For the \( m \) value in the equation, according to Churchill’s study, when the PV module tilt angle \( \beta \geq 15^\circ \), \( m = 3 \) and when the PV module tilt angle \( \beta < 15^\circ \), \( m = 3.5 \) [13]. After calculating \( Nu_{\text{all}} \), the total convection heat transfer coefficient of the front and back panels of the PV module can be obtained according to Nusselt criterion.

2.3. Radiation heat transfer of photovoltaic modules

According to the law of Boltzmann radiation heat transfer, the radiation heat transfer coefficient of the front and back panels of the PV module can be calculated by using the following equations [14]:

\[
\begin{align*}
 h_{r,f} &= \varepsilon_f \times X_{f\text{-sky}} \times \sigma \times (T_{f\text{PV}}^2 + T_s^2) (T_{f\text{PV}} + T_s) + \\
 h_{r,b} &= \varepsilon_b \times X_{b\text{-sky}} \times \sigma \times (T_{b\text{PV}}^2 + T_s^2) (T_{b\text{PV}} + T_s) + \\
 h_{r,\text{ground}} &= \varepsilon \times X_{\text{ground}} \times \sigma \times (T_{\text{PV}}^2 + T_{\text{grid}}^2) (T_{\text{PV}} + T_{\text{grid}})
\end{align*}
\]

(15)

where, \( \varepsilon_f \) represents thermal radiation coefficient of the front panel of PV modules; \( \varepsilon_b \) is thermal radiation coefficient of the back panel of PV modules; \( \sigma \) is Boltzmann constant which is \( 5.67 \times 10^{-8} \) W m\(^{-2}\) K\(^{-4}\); \( T_s \) is sky temperature, \( T_s = 0.0552 \times T_a^{1.5} \), K; \( T_{\text{grid}} \) is ground temperature, \( T_{\text{grid}} = T_s, K; X_{f\text{-sky}}, X_{f\text{-ground}} \) are angle factors between the front panel and sky and ground, respectively; \( X_{b\text{-sky}}, X_{b\text{-ground}} \) are angle factors between the back panel and sky and ground, respectively, which are calculated by using the following equations:

\[
X_{f\text{-sky}} = (1 + \cos \beta) / 2
\]

(17)

\[
X_{f\text{-ground}} = (1 - \cos \beta) / 2
\]

(18)

\[
X_{b\text{-sky}} = (1 + \cos (\pi - \beta)) / 2
\]

(19)
2.4. Establishment of the mathematical model for the temperature of photovoltaic modules

Substituting Equations (2)–(8) into Equation (1) results in:

\[ \tau I_T A \phi dt = \tau I_T A \eta_{ref} \left[ 1 - \beta_{ref} \left( T_{PV} - T_{ref} \right) \right] dt + U_{L,f} \]
\[ \times (T_{PV} - T_s) Adt + U_{L,b} \times (T_{PV} - T_s) Adt + C \cdot dT \]

Equation (21) is divided by \( dt \) on both sides to obtain:

\[ \tau I_T A \phi = \tau I_T A \eta_{ref} \left[ 1 - \beta_{ref} \left( T_{PV} - T_{ref} \right) \right] + U_{L,f} \times (T_{PV} - T_s) A + U_{L,b} \times (T_{PV} - T_s) A \]

\[ \tau T/\tau dt = \tau I_T A \phi \left[ 1 - \beta_{ref} \left( T_{PV} - T_{ref} \right) \right] + U_{L,f} \times (T_{PV} - T_s) A + U_{L,b} \times (T_{PV} - T_s) A \]

In Equation (22), \( dT/\tau dt \) represents the rate of change of the PV module temperature over time. When analyzing the influence of environmental factors on the temperature of the PV module, it is necessary to analyze the module temperature in a stable state, that is, the temperature should remain the same in this period, i.e., \( dT/\tau dt = 0 \), then Equation (22) can be written as follows:

\[ \tau I_T A \phi = \tau I_T A \eta_{ref} \left[ 1 - \beta_{ref} \left( T_{PV} - T_{ref} \right) \right] + U_{L,f} \times (T_{PV} - T_s) A + U_{L,b} \times (T_{PV} - T_s) A \]

This does not take into account the effect of dust deposition, thus the light transmission rate can be considered as 100%; and the module tilt angle is set as 30°. Some of the parameters in the equation were provided by the equipment manufacturer (the experimental system in Section 3) as follows: the absorption rate of the solar cell was 0.92; the thermal radiation coefficient \( \epsilon_f \) of the front glass panel was 0.85; the thermal radiation coefficient \( \epsilon_b \) of the back panel was 0.95; the efficiency of the PV module used in this experimental platform under standard test conditions \( \eta_{ref} \) was 14.98%; the temperature coefficient \( \beta_{ref} \) of the module was \(-0.45%/°C\); and the operating temperature of the module under standard test conditions was 25 °C. Moreover, the thermal properties parameters of the air in the normal temperature range did not change too much and thermal physical parameters at 25 °C were used as a benchmark.

In Equation (23), when the meteorological parameters including the solar radiation intensity, ambient temperature, and wind speed are known, there is only one unknown \( T_{PV} \), which can be accordingly calculated.

3. Photovoltaic experimental system

3.1. Photovoltaic experimental platform

The experimental platform, with a total area of 489 m², was built in a factory area of Chang'an District, Xi'an. The PV module array contained 6 series, and there were 9 PV modules in each series. The photograph of the experimental field is shown in Fig. 1(a). The PV modules used in the experiment were selected from polycrystalline silicon products produced by JA Solar. Under standard test conditions, the output power of PV modules was 245 W, the module efficiency was 14.98%, the PV module temperature coefficient was \(-0.45%/°C\), and the PV module size (height \times width \times thickness) was 1650 mm \times 990 mm \times 40 mm. For more information, see reference [15].

3.2. Photovoltaic experimental detecting system

For an accurate and real-time detection of temperature data, a temperature acquisition system consisting of T-type thermocouple and CR1000 collector was established. The thermocouple was arranged on the back of the PV module as shown in Fig. 1(b), and data acquisition and real-time detection were conducted by using LoggerNet software. The measuring system was operated under a temperature range of \(-20 \) to 350 °C with a measurement error of ± 0.1°C.
The meteorological parameters of the experimental field were measured using an RSR1000 rotary solar measurement system, which was installed next to the PV experimental field, as shown in Fig. 1(c). The measurement system accurately measures the total radiation, direct radiation, and scattered radiation in the horizontal plane, and total radiation at 30° and 35° dip plane. Moreover, it can also measure the atmospheric temperature, humidity, wind speed, and so on.

Fig. 1 Experimental system

4. Validation of mathematical model

The as-established mathematical model indicates that temperature of PV modules is related to ambient temperature, solar radiation intensity, and wind speed. In this section, the mathematical model described in the previous section is verified by the in-situ experimental methods.

4.1. Basic conditions

The PV platform experiment system was operated under no-load conditions by December 31, 2014, with an output power of 0; and then grid was connected to operate under load conditions. The mathematical model described in the previous section was verified under no-load and load conditions, respectively.

The mathematical model discussed in the previous section, as represented by Equation (23), was based on the load conditions. When the mathematical model is validated under no-load conditions, the power generation represented by Equation (23) should be changed to zero.

In the meteorological parameter measurement system, the wind speed was measured at a height of 10 m from the ground, which refers to the wind speed flowing through the surface of PV modules. Therefore, the wind speed of the measuring point was converted to the wind speed near the ground, and the wind speed of 1 m away from the ground was the wind speed flowing through the modules. The conversion equations are as follows [16]:

\[
\frac{V_w}{V_m} = \left(\frac{Z_w}{Z_m}\right)^n
\]

\[n = \frac{0.37 - 0.0881 \cdot \ln(V_m)}{1 - 0.0881 \cdot \ln(Z_m/10)}
\]

where, \(V_w\) represents the wind speed flowing through the PV modules (m s\(^{-1}\)); \(Z_m\) is the height of the measurement point from the ground, i.e. 10 m; \(V_m\) is the measured speed (m s\(^{-1}\)); and \(Z_w = 1\) m.

In this study, the data of the temperature of PV modules and meteorological parameters were obtained by in-situ experiments. First, the measured ambient temperature \(T_a\), wind speed \(V_w\), and solar radiation intensity \(I_T\) on the surface of modules were substituted in Equation (23) to calculate the temperature of PV modules, which was then compared with the actual measured temperature of modules. Herein the measured temperature of PV modules was considered as the average temperature of the intermediate measuring point of back panel of the PV module in the middle of six groups.
4.2. Validation of the mathematical model under no-load conditions

During the verification of the mathematical model Equation (23), in order to minimize the interference of dust and other factors on the experimental results, the time period when the weather was clear with little air pollution after heavy rain was selected for analysis.

Through the analysis of the experimental data, it was found that on October 16, 2014 it rained heavily (the rain is considered to wash and clean PV components, and the role of dust is not considered), and on the second day it was sunny. According to the meteorological parameters (Fig. 2) obtained on October 17, the mathematical model was used to predict the temperature of PV modules. The comparison between the calculated value $T_1$ and experimental value $T_s$ is shown in Fig. 3. Clearly, the calculated values are consistent with the experimental values. In most cases the calculated values were slightly smaller than the experimental values; however, the maximum error was within 2 °C, while the average relative error was 7.8%, and the maximum relative error was 15.3% at 3:13 pm.

4.3. Validation of the mathematical model under load conditions

In the following study, the established mathematical model was verified under the load conditions. Similar to the model under no load condition, in order to minimize the interference of dust and other factors on the experimental results, the time period when the weather was clear with little air pollution after heavy rain was selected for analysis. Through the analysis of the experimental data, it was found that the experimental data of three days April 5th to 7th met the required conditions (on April 4th it rained heavily, while on April 5th to 7th, it was sunny and the solar radiation intensity was large at noon).

According to the meteorological parameters obtained from April 5th to 7th (Fig. 4), the comparison between the operating temperature of PV modules calculated by the thermal equilibrium model Equation (23) and the measured operating temperature of PV modules is shown in Fig. 5. Clearly, the trend of the calculated value $T_1$ is similar to that of the measured value $T_s$, and the calculated value is slightly lower than the experimental value. They were basically close and the maximum error was within 2 °C, while the average relative error was 4.8%, and the maximum relative error was 11.49% at 1:36 pm on April 5.
The above mentioned analysis indicates that the mathematical model Equation (23) is reliable under both the no-load conditions and the load conditions, and can be effectively used to predict the temperature of PV modules.

Fig. 4 Change of meteorological parameters from April 5th to 7th

Fig. 5 Comparison between the experimental value $T_s$ and calculated value $T_1$ of the operating temperature of PV modules obtained from April 5th to 7th

5. Conclusions
Based on the basic knowledge of physics and the empirical equations in the field of photovoltaic (PV) power generation, the mathematical model representing relationship between PV module temperature and ambient temperature, solar radiation intensity, and wind speed was established based on thermal equilibrium analysis. Through the measured data by the established experimental platform, the as-designed mathematical model was verified under no-load and load conditions, respectively.

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