Dynamic modeling and practical verification of a photovoltaic and thermal composite module system

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Abstract. In order to further improve the prediction accuracy of PV/T module temperature, this paper conducts dynamic modeling of PV/T module heat transfer mechanism based on lumped parameter method. The accuracy of the dynamic model was verified by experiments on typical sunny and cloudy days. The experimental results show that the maximum relative errors of the predicted values in sunny and cloudy weather are 7.8% and 7.6% respectively. The average relative errors were 4.31% and 4.37% respectively. The average absolute error is 2.04°C, 1.94°C. Compared with the existing neural network prediction methods, the mathematical model has higher prediction accuracy and shorter prediction period. This model can be used for PV/T system to formulate accurate control strategy in advance according to the temperature change situation, so as to optimize the energy saving during system operation. It can also be used for establishing the overall energy transfer model of PV/T system, realizing the coordinated control of thermal energy and electric energy and the cascade utilization of solar energy.

1. Introduction

Solar energy is a kind of renewable energy with abundant amount and wide coverage. In recent years, the gradual expansion of the scale of solar energy use has accelerated the technological upgrading of related industries, and the application of solar energy in the field of building energy in China also shows great potential for promotion [1]. But subject to the material physical properties limited, including monocrystalline silicon, polycrystalline silicon photovoltaic (PV) components for solar energy conversion rate is still less than 20%, the temperature rise of the sun brings further reduce its power generation efficiency, therefore, photovoltaic photothermal system which integrates power generation and heat storage functions has attracted more and more attention [2-3].

PV/T system mainly includes the PV/T components heat storage water tank water pump and so on, the running of the whole system is directly affected by the weather change. The short-term prediction of PV/T component temperature facilitates the formulation of accurate control strategies during PV/T system operation to optimize energy saving during system operation. At present, PV/T component temperature prediction methods can be roughly divided into two categories [4]: firstly, the historical temperature and real-time environmental data of photovoltaic panels were collected, and then the PV/T
module temperature was predicted by the algorithm. In the Literature [5], sample data of ambient temperature and irradiance are chosen to establish statistical model, through the regression analysis can make a rough prediction of PV components temperature. In the literature [6] BP neural network are trained by the temperature history data to set up a forecasting model without considering the environment parameters. The model requires high accuracy of historical data and some weather prediction errors are large. In the literature [7], the principal component that affects the PV/T module temperature is proposed through principal component analysis of the original data, a dynamic prediction model is established by combining feedback Elman neural network. The use scenario of the model is limited because of not taking into account the dynamic behavior of PV/T system cooling the Solar cell with water. Secondly, adynamic thermal models of PV/T component was established to realize temperature prediction. Koech [8] has earlier proposed the steady-state thermal model of PV/T air solar collector, which has been verified by experimental data and used to evaluate the influence of various parameters on system performance. Mattia and Giorgio [9] derived a dynamic thermal model for hybrid PV panels to reproduce the short-term dynamic characteristics of PV/T components, and verified the model with experimental data collected during outdoor testing at the University of Genoa. Because the model ignores part of the hierarchical structure, the overall prediction effect is poor. Chung-feng [10] et al. built a heat transfer model of PV/T system PV modules based on lumped heat capacity method, and comprehensively considered environmental factors such as ambient temperature, wind speed and solar radiation, improving the accuracy of temperature, electrical efficiency and heat storage efficiency prediction. However, the modeling of water cooling process does not consider the influence of laminar flow and turbulent flow on heat transfer, but only roughly estimates the difference between inlet and outlet water temperature, which has certain influence on the accuracy of the model.

In this paper, the heat transfer structure of PV/T module is analyzed based on the actual situation of the experimental platform, and the EVA layer with small thickness and poor heat transfer performance is ignored. Secondly, the calculation method of forced convection heat exchange is introduced to accurately calculate the heat exchange amount during the cooling process of water-cooled PV/T system. Then, according to Lumped parameter method, the heat balance equation of each layer structure of PV/T module and the thermal model of PV/T system are established, and the simulation model is established by Simulink software tool. Finally, the correctness of the PV/T system dynamic model is verified by the PV/T system experimental platform built in Nanning, Guangxi.

2. Introduction to water-cooled PV/T system

In this paper, the water-cooled PV/T system is studied, as shown in Fig. 1. The water pump in the water tank is controlled by the controller to cool the water pump to the PV/T component and continuously circulate. The temperature of the PV/T component is reduced while the heat is accumulated, so as to improve its power generation efficiency and realize the comprehensive utilization of heat energy and electric energy.

**Figure 1.** Schematic diagram of PV/T system. **Figure 2.** Structure of PV/T module.
Fig. 2 is the PV/T module longitudinal structure diagram. From top to bottom, it is glass cover layer, photovoltaic cell layer, solar cell back film (TPT) layer, aluminum foil layer and copper tube layer.

3. Lumped parameter method

The water-cooled PV/T system is a typical unsteady state thermal conductivity problem in operation, which can be reduced to a definite solution problem consisting of a differential equation of thermal conductivity containing unsteady state terms and corresponding single value conditions. It is very difficult to solve this kind of problem completely from the point of view of analytical solution. Lumped parameter analysis method, referred to as lumped parameter method, takes the whole object as a particle, regardless of volume and mass, and considers that it has only one temperature value at the same time. It approximately ignores the thermal conductivity of the object and thus simplifies the solution of transient thermal conductivity problem.

The follow is the application condition of lumped parameter method:

\[ Bi = \frac{hL}{k} < 0.1 \]  

Where \( Bi \) is the behavior number, \( h \) is the surface heat transfer coefficient, \( k \) is the thermal conductivity coefficient and \( L \) is the thickness. After consulting relevant parameters and calculating, the behavior number of each layer structure of PV/T component in this paper is far less than 0.1, so lumped parameter method can be used to analyze its dynamic characteristics.

Based on the law of conservation of heat energy, lumped parameter method establishes the balance equation between heat capacity at both ends of the object and heat flow caused by different heat transfer mechanisms [11].

\[ C = \frac{dT}{dt} = q_{con} + q_{cov} + q_{ra} \]  

Where \( C \) is the heat capacity, \( q_{con} \) is the conductive heat flow, \( q_{cov} \) is the convective heat flow and \( q_{ra} \) is the radiation heat flow.

The heat capacity is expressed as:

\[ C = \rho ALc \]  

Where \( \rho \) is the density, \( A \) is the area, \( L \) is the thickness and \( c \) is the specific heat capacity.

3.1. Conductive heat flow

There are three basic forms of heat transfer from one substance to another: heat conduction, heat convection, and heat radiation. Conduction heat flow is the heat flow transmitted through the form of heat conduction, and its expression is shown as below:

\[ q = \frac{\Delta T}{\theta} \]  

Where \( \Delta T \) is the temperature difference value of two kinds of objects in which heat conduction occurs, \( \theta \) is the thermal resistance which can be calculated from Eq. (5).
\[ \theta_{\text{con}} = \frac{L}{kA} \]  

(5)

3.2. Convective heat flow

The convection heat transfer involved in this paper includes the connection between the air flowing in the environment and the surface of the glass layer, as well as the connection between the water flow in the copper pipe and the copper pipe wall. The former can be calculated by Eq. (4), in which the expression of the convection heat resistance is shown as Eq. (6).

\[
\theta_{\text{cov,fg}} = \frac{1}{(h_{\text{forced}} + h_{\text{free}})A}
\]

(6)

Where \( h_{\text{forced}} \) and \( h_{\text{free}} \) are forced convection coefficient and free convection coefficient respectively? In this paper, the value of \( h_{\text{forced}} \) is 11.4, the value of \( h_{\text{free}} \) is 5.4W, and that of \( W \) is wind speed.

The connection between the water inside the copper tube and the copper tube belongs to forced convection, and its heat flow expression is

\[
q_{cp} = hA_{cp}\Delta t_m
\]

(7)

\[
h = Nu_{\text{f}} \frac{k}{d}
\]

(8)

\[
Nu_f = 0.023Re_f^{0.8} Pr_f^{0.4}
\]

(9)

\[
Re_f = \frac{4qv}{\pi \nu d}
\]

(10)

\[
A_{cp} = \pi dl
\]

(11)

\[
\Delta T_m = \frac{(T_{cp} - T_{m,i}) - (T_{cp} - T_{m,o})}{\ln[(T_{cp} - T_{m,i}) / (T_{cp} - T_{m,o})]}
\]

(12)

Where \( d \) is the diameter, the diameter of copper tube in this paper is 0.008m. \( Nu_f \) is the nusselt number, it is related to the form of convection, which is calculated by Eq. (9). \( Pr_f \) is prandtl number, which is related to temperature, and is set as 0.45 in this paper. \( Re_f \) is the Reynolds number. \( q \) is the mass flow rate. \( \nu \) is the unit of kinematic viscosity, set as \( 0.7 \times 10^{-6} \text{ m}^2 / \text{s} \) in this paper. \( A_{cp} \) is the inner surface area of the copper tube. \( l \) is the length, the total length of copper tube in this paper is 15m. \( T_{cp} \) is the temperature of copper tube. \( T_{m,i} \) and \( T_{m,o} \) represents the average temperature of the fluid at the tube inlet and outlet sections, respectively.
3.3. Radiant heat flow
Radiation heat flow can be divided into short-wavelength radiation heat flow and long-wavelength radiation heat flow, the former generally comes from the sun, high temperature objects and other radiation sources, the calculation formula is

\[ q_{abs} = AG\alpha \]  

(13)

Where \( G \) is external projected radiation, \( \alpha \) is the radiation absorption ratio, \( \alpha_{fg} \) and \( \alpha_{pv} \) are the absorption ratios of glass layer and photovoltaic cell layer to solar radiation, they are set as 0.5 and 0.9 respectively.

The calculation formula of long wavelength radiation heat flow is shown as below:

\[ q_v = A\varepsilon\sigma(T_w^4 - T_{sur}^4) \]  

(14)

Where \( \varepsilon \) is the emissivity of radiation, the radiant emissivity of the glass layer in this paper is 0.85. \( \sigma \) is Boltzmann constant, whose value is \( 5.6697 \times 10^{-8} \) W/(K^4·m^2). \( T_w \) is the surface temperature of the object. \( T_{sur} \) is the ambient temperature.

4. Dynamic modeling of PV/T COMPONENT

4.1. Modeling assumptions
(1) The temperature distribution of each layer of PV/T component is distributed uniformly, which can accurately simulate the heat transfer process in one dimension.

(2) The heat conduction of the aluminum structural frame which externally mount PV/T component is ignored because its area is much smaller than the transverse area.

(3) In PV/T module, the EVA layer under the photovoltaic panel is too thin and its thermal conductivity is far less than that of other layer structures, so its heat conduction is ignored.

4.2. Establishment of dynamic thermal model
The heat transfer mechanism of each layer structure of PV/T component was analyzed after considering the hypothesis. Heat transfer in the glass layer of the outermost structure includes the short-wavelength radiation heat flow caused by solar irradiation, the convection of air caused by wind speed, the long-wavelength radiation heat flow with the environment and the conduction heat flow with the photovoltaic cell layer. The sunlight radiates to the photovoltaic cell through the glass, so the photovoltaic cell layer has a thermal radiation mechanism in addition to heat conduction. The contact between the layers within the PV/T module is a heat transfer mechanism affected by thermal resistance and temperature difference. The bottom layer is the copper tube layer, the heat transfer in addition to the aluminum foil layer has heat conduction and heat convection caused by the water flow driven by the water pump in the copper tube. According to the above analysis, the heat balance equation of each layer structure of PV/T component can be obtained by lumped parameter method.

Glassy layer:

\[ \rho_{fg}A_{fg}L_{fg}C_{fg} \frac{dT_{fg}}{dt} = \frac{T_{pv} - T_{fg}}{\theta_{con, pv}} + \frac{T_{sur} - T_{fg}}{\theta_{cov, fg}} + A\alpha_{fg}G - A\varepsilon\sigma(T_{fg}^4 - T_{sur}^4) \]  

(15)

Photovoltaic cell layer:
\[ \rho_{pv} A_{pv} L_{pv} c_{pv} \frac{dT_{pv}}{dt} = \frac{T_{fg} - T_{pv}}{\theta_{con, pv}} + \frac{T_{t} - T_{pv}}{\theta_{con, t}} + \tau_{fg} A_{pv} \alpha_{pv} G \] (16)

Where \( \tau_{fg} \) is the transmittance of glass layer to solar short-wave radiation, set as 0.85.

**TPT layer:**

\[ \rho_{Al} A_{Al} L_{Al} c_{Al} \frac{dT_{Al}}{dt} = \frac{T_{pv} - T_{t}}{\theta_{con, t}} + \frac{T_{Al} - T_{t}}{\theta_{con, Al}} \] (17)

**Aluminum foil layer:**

\[ \rho_{Al} A_{Al} L_{Al} c_{Al} \frac{dT_{Al}}{dt} = \frac{T_{t} - T_{Al}}{\theta_{con, Al}} + \frac{T_{cp} - T_{Al}}{\theta_{con, cp}} \] (18)

**Copper layer:**

\[ \rho_{cp} A_{cp} L_{cp} c_{cp} \frac{dT_{cp}}{dt} = \frac{T_{Al} - T_{cp}}{\theta_{con, cp}} - h A_{cp} \Delta t_m \] (19)

At this point, the dynamic thermal model of PV/T component has been established, and the input parameters of each layer structure of PV/T component are shown in Table 1[12]. Using Simulink software tools to establish the above differential equations model can be solved.

| Parameters                      | Glass | Photovoltaic Cell | TPT   | Aluminium Foil | Copper | Water |
|---------------------------------|-------|-------------------|-------|----------------|--------|-------|
| \( \rho/g\cdot(\text{cm}^3) \)  | 3000  | 2330              | 1200  | 2698           | 8920   | 1000  |
| \( A/m^2 \)                     | 0.7955| 0.7955            | 0.7955| 0.7955         | 0.1905 | /     |
| \( L/m \)                       | 0.003 | 0.0003            | 0.0005| 0.0012         | 0.0127 | /     |
| \( c/J\cdot(\text{kg} \cdot ^\circ\text{C}) \) | 500   | 677               | 1250  | 880            | 385    | 4200  |
| \( k/W\cdot\text{m}^{-1}\cdot\text{K}^{-1} \) | 1.1   | 130               | 0.033 | 237            | 401    | 0.6   |

5. Analysis of simulation examples

5.1. Experimental data collection

In this paper, the PV/T system experimental platform is built in Nanning, Guangxi. The main data collected by the data acquisition program written by LabVIEW software include the temperature of Solar cell, the water temperature at the entrance and exit of Solar cell, the mass flow rate of cooling water in copper tubes, the water temperature of the heat collecting tank and various environmental data such as ambient temperature \( T_{\text{sur}} \), solar irradiance \( G \), wind speed \( W \), etc.

According to the weather forecast, this paper selects August 13 and August 27, 2018 as the sunny weather and cloudy weather experimental days respectively. PV/T system runs from 6 am to 6 PM. The data acquisition system collects data every 20 seconds and stores them into the database. At about 10 o'clock in the morning, the pump is turned on, and after 10 minutes of water cooling, the temperature of the photovoltaic panel decreases significantly and gradually becomes stable. In this paper, the above
two typical weather data were selected and substituted into PV/T component dynamic heat transfer model to verify its accuracy.

5.2. Prediction accuracy evaluation criteria
In this paper, relative error RE, absolute error mean MAE and mean absolute percentage error MAPE are used to evaluate the prediction accuracy of PV/T component dynamic thermal model. The calculation formulas of the three are respectively shown as:

\[
RE = \left| \frac{\bar{Y} - Y}{Y_i} \right| \times 100\% \tag{20}
\]

\[
MAE = \frac{1}{n} \sum_{i=1}^{n} \left| \bar{Y} - Y_i \right| \tag{21}
\]

\[
MAPE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{\bar{Y} - Y_i}{Y_i} \right| \times 100\% \tag{22}
\]

Where \(Y_i\) the real value, \(\bar{Y}_i\) the predicted value of the mathematical model, \(n\) is the number of model iterations.

5.3. Analysis of prediction results
The above mathematical model is built in Simulink software, and various known parameters such as \(\rho\), \(A\), \(L\), \(c\), \(k\) are input. Before each calculation, the ambient temperature \(T_{\text{sur}}\), solar irradiance \(G\), and wind speed \(W\) collected by the data collection system are input, so that the structural temperature values of each layer of PV module can be obtained, and then the dynamic changes of the structural temperature of each layer can be obtained through continuous iteration. Fig. 3 and Fig. 4 are the predicted and actual Solar cell temperatures of the mathematical model under sunny and cloudy conditions respectively. Fig. 5 shows the relative error values of the prediction results under sunny and cloudy conditions.

![Figure 3. Forecast results in sunny days](image1)

![Figure 4. Forecast results in cloudy days](image2)
Figure 5. Relative forecast error under two weather conditions

As can be seen from Figs. 3 and Figs. 4, the relative error of the predicted value of the mathematical model is within 10% under both sunny and cloudy conditions, and the accuracy is greatly improved compared with the algorithm prediction [7]. The mathematical model based on Lumped parameter method can accurately predict the temperature of Solar cell during the cooling process of water-cooled PV/T system. As can be seen from Figure. 5, the relatively large error values are concentrated in the two stages of starting to cool down and the Solar cell temperature tends to stabilize, which may be caused by the inaccurate setting of the initial value and the rapid temperature rise of the heat storage tank. Table 2 shows various evaluation indexes of prediction errors of mathematical models under two weather conditions.

|               | RE-MAX/% | RE-MIN/% | MAPE/% | MAE/°C |
|---------------|----------|----------|--------|--------|
| Sunny         | 7.8      | 0.4      | 4.31   | 2.04   |
| Cloudy        | 7.6      | 0.5      | 4.37   | 1.94   |

6. Conclusion
After reasonable assumptions are made, the heat transfer mechanism of PV/T module layers is analyzed in detail. Three heat transfer modes including heat conduction, heat convection and heat radiation are considered. Based on Lumped parameter method, the heat conservation equation of PV/T module layers and the overall dynamic model are established. The accuracy of the dynamic model is verified by selecting typical sunny days and cloudy days for experiments. The experimental results show that the maximum relative error, the average relative error and the average absolute error of the prediction value of the mathematical model are 7.8%, 4.31% and 2.04°C respectively in sunny weather. The maximum relative error, average relative error and absolute error of the predicted value of the mathematical model under cloudy weather are 7.6%, 4.37% and 1.94°C respectively. Compared with the existing neural network prediction methods, the mathematical model established in this paper not only has higher prediction accuracy, but also greatly shortens the prediction time. The model can be used to formulate precise control strategies for PV/T system operation and provide technical support for optimizing energy saving during system operation. It can also be used to establish the overall energy...
transfer model of PV/T system to realize coordinated control of thermal energy and electric energy and cascade utilization of solar energy.

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