Research on applications of phase change materials in solar cell thermal control

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Abstract. In order to grasp the characteristics of phase change material (PCM) in solar cell thermal control, a two-dimensional thermal control structure model of PV/PCM solar cell thermal control system was established, and study was conducted on influence of PCM phase change temperature, thermal conductivity, latent heat value, etc. on the temperature control characteristics of solar cells. The results show that PCM phase change temperature, thermal conductivity, latent heat value will affect solar cell temperature control characteristics in varying degrees. At the same time, thermal control characteristics of PCM are greatly affected by environmental meteorological conditions (solar irradiance, ambient temperature). The research results provide a reference for optimization design of PV/PCM solar cell thermal control system.

1. Introduction
In the photovoltaic power generation process, most solar energy absorbed by the solar cell is converted into thermal energy, making its own temperature continuously increased, and the electrical efficiency is reduced by about 0.45% for every 1°C increase in the temperature of the crystalline silicon solar cell [1,2]. Therefore, controlling operating temperature of solar cell is one of the keys to improving photovoltaic power generation efficiency of the solar cell. Study on solar cell thermal control can be traced back to 1978 when Russell et al. proposed the concept of PV/T solar collectors [3]. Later, many scholars have studied PV/T theory and technology [4]. Among them, PV/PCM technology and theory using phase change heat storage to control solar cell temperature has become a new research field [5-8]. For example, Huang et al used 1D, 2D and 3D finite element analysis methods to analyze thermal and electrical properties of the PV/PCM solar system under different parameters, revealing that the output of the PV system can be increased by 6% in some areas [9-11]. Park et al designed a PV/PCM experimental setup, and the experiment showed that PV cell temperature in PV/PCM systems was 5°C lower than conventional PV modules, and the conversion efficiency was improved by about 3.1% [12]. Maiti et al used a paraffin phase change material with a melting range of 56-58°C to control operating temperature of the photovoltaic cell. In indoor, within 3 hours under irradiance of 2300 W/m², the temperature of the photovoltaic cell could be maintained at 65-68°C; in outdoor, under natural conditions, temperature of photovoltaic cells could be reduced from 78°C to 62°C, the output power of photovoltaic cells was significantly improved [13]. For the PV/PCM system designed by Hasan et al, it was found that the solar cell temperature was maximally reduced by 18°C within 30 min and reduced by 10°C within 5h under the condition of 1000 W/m² [14].
The above research indicates that PCM has important development potential in solar cell thermal control, but its application is still in its infancy, and further study is needed on the influence of PCM thermal characteristics on solar cell temperature control characteristics and its physical mechanism. In this paper, PV/PCM thermal control structure model is established to study the influence of phase change temperature, thermal conductivity and phase change enthalpy of PCM on solar cell temperature control characteristics, which provides a reference for optimization design of PV/PCM solar thermal control system.

2. PV/PCM structure model for phase change material thermal control

The PV/PCM solar cell thermal control model consisting of phase change materials mainly includes solar cells, phase change materials, package casings (aluminum boxes), and thermal silica gel between the solar cells and the package casing. A schematic diagram of the two-dimensional geometric model and heat transfer of the PV/PCM solar thermal control system is shown in figure 1:

![Figure 1. PV/PCM structure model and heat transfer diagram.](image)

In the PV/PCM system, most solar energy radiated to the surface of solar cell is absorbed and converted into thermal energy. Wherein, a part is stored in the PCM, and a part is dissipated into the environment through the solar cell and the package casing. The storage and transmission of thermal energy in the PV/PCM thermal control system is shown in figure 1.

According to the energy balance theorem, the thermal energy $Q_A$ converted by the solar cell is equal to the sum of storage thermal energy $Q_{st}$ of the phase change material and heat $Q_l$ of PV/PCM system dissipated to the surrounding environment.

$$Q_A = Q_{st} + Q_L$$

Among them, energy $Q_l$ of PV/PCM thermal control system dissipated into the surrounding environment includes three parts: top heat loss $Q_{tp}$, bottom heat loss $Q_{tb}$ and side heat loss $Q_{ts}$, namely:

$$Q_l = Q_{tp} + Q_{tb} + Q_{ts}$$

In addition, the heat storage process of the phase change material can be classified based on solid phase region and liquid phase region. In the solid phase region of PCM, the heat flow is transmitted by heat conduction, and the energy differential equation is the heat conduction equation, that is,

$$\rho_s C_s \frac{\partial T_s}{\partial t} = \nabla \cdot (k_s \nabla T_s) + Q_s$$

Where, $\rho_s$ is the solid phase region density ($\text{kg/m}^3$); $C_s$ is specific heat capacity of the solid phase region ($\text{J/(kg K)}$); $T_s$ is the solid phase region temperature (K); $k_s$ is thermal conductivity coefficient of the solid phase region ($\text{W/(m}^2\text{K)}$); $Q_s$ is volumetric source of solid phase region ($\text{W/m}^3$).

In the liquid phase region of the phase change material, in addition to heat transfer, there may be
convective transfer of heat flow. Therefore, the energy differential equation in the liquid region also contains the convection term, and the equation is:

$$\rho_l C_l \left( \frac{\partial T_l}{\partial t} + \mathbf{v} \cdot \nabla T_l \right) = \nabla \cdot (k_l \nabla T_l) + Q_l$$

Where, $\mathbf{v}$ is the kinematic viscosity ($\text{m}^2/\text{s}$); $\rho_l$ is the liquid phase region density ($\text{kg/m}^3$); $C_l$ is specific heat capacity of the solid phase region ($\text{J/(kg}$·$\text{K}$)); $T_l$ is the solid phase region temperature ($\text{K}$); $k_l$ is thermal conductivity coefficient of the solid phase region ($\text{W/(m}^2 \cdot \text{K}$)); $Q_l$ is volumetric source of solid phase region ($\text{W/m}^3$).

### 3. PV/PCM material and structural parameters

Taking the lauric acid-stearic acid composite phase change material as a reference, the thermal conductivity and density of the phase change material did not change after the phase change, and the heat capacity at constant pressure of the material was consistent with the heat capacity at constant volume. The parameters are shown in tables 1 and 2. According to the actual model structure, the structural parameters of the PV/PCM system are designed as shown in table 3.

**Table 1.** Performance parameters of PCM before phase change.

| Heat capacity at constant pressure (J/(kg·K)) | Density ($10^3$ kg/m$^3$) | Specific heat rate (J/g) | Latent heat value (J/g) | Thermal conductivity coefficient (W/(m·K)) |
|---------------------------------------------|-----------------------------|-----------------|----------------------|----------------------------------|
| 2340                                        | 0.9408                      | 1               | 200                  | 1                                |

**Table 2.** Performance parameters of PCM after phase change.

| Heat capacity at constant pressure (J/(kg·K)) | Density ($10^3$ kg/m$^3$) | Specific heat rate (J/g) | Latent heat value (J/g) | Thermal conductivity coefficient (W/(m·K)) |
|---------------------------------------------|-----------------------------|-----------------|----------------------|----------------------------------|
| 2340                                        | 0.9408                      | 1               | 200                  | 1                                |

**Table 3.** Model structure parameters.

| Parameter                                  | Value | Parameter                            | Value |
|--------------------------------------------|-------|--------------------------------------|-------|
| Solar cell thickness /cm                   | 0.3   | PCM layer thickness / cm              | 4     |
| Thermal silica gel layer thickness / cm    | 0.1   | Aluminum hell thickness / cm          | 0.2   |
| Environmental temperature T$_0$/°C         | 18    | Solar irradiance (W/m$^2$)            | 800   |

### 4. Analysis of the influence of PCM thermophysical parameters on thermal control characteristics

#### 4.1. Influence of PCM phase change temperature on solar cell thermal control characteristics

According to the material and structural parameters of the PV/PCM system as shown in tables 1, 2 and 3, under ambient temperature of 18°C and irradiance of 800 W/m$^2$, 900 W/m$^2$, and 1000 W/m$^2$, the influence of PCM phase change temperature on solar cell temperature control characteristics is shown in figure 2:
As shown in Figure 2, under the ambient temperature of 18°C, PCM phase change temperature has a significant effect on solar cell temperature control. For example, under the irradiance of 800 W/m², PCM with phase change temperature of 30°C can control solar cell temperature below 47°C for 8818 s; PCM with phase change temperature of 40°C can control solar cell temperature below 47°C for 6330 s. In addition, the thermal control effect of PCM phase change temperature on solar cell temperature is greatly affected by irradiance. For example, when the PCM phase change temperature is 30°C and irradiance is 800 W/m², the solar cell temperature reaches 44.2°C in 2 h; when the irradiance is 900 W/m², 1000 W/m², the solar cell temperature reaches 46.58°C and 51°C respectively in 2 h.

4.2. Influence of PCM phase change heat enthalpy on solar cell thermal control characteristics

According to the material and structural parameters of the PV/PCM system as shown in tables 1, 2 and 3, under ambient temperature of 18°C, PCM phase change temperature of 50°C and irradiance of 800 W/m², 900 W/m², 1000W/m², the influence of PCM phase change enthalpy on solar cell temperature control characteristics is shown in Figure 3:

It can be seen from Figure 3 that for a greater PCM phase change enthalpy, the thermal control effect on the solar cell is better. For example, under irradiance of 800 W/m², PCM with a phase change enthalpy of 150 J/g can control the solar cell temperature below 57°C for 7606 s, and PCM with a phase change enthalpy of 300 J/g can control the solar cell temperature below 57°C for 9553 s. In addition, the thermal control effect of phase change enthalpy of phase change material on solar cell is also affected by solar cell irradiance. PCM with the same phase change enthalpy has better temperature control effect when the irradiance is smaller. For example: under PCM phase change enthalpy of 150 J/g and irradiance of 800 W/m², 900 W/m² and 1000 W/m², PCM can control the solar cell temperature below 57°C for 7606 s, 6882 s and 5936 s, respectively.
4.3. Influence of PCM thermal conductivity on thermal control characteristics of solar cells

According to the material and structural parameters of the PV/PCM system as shown in tables 1, 2 and 3, under ambient temperature of 18°C, PCM phase transition temperature of 50°C and irradiance of 800 W/m², 900 W/m² and 1000 W/m², the influence of PCM thermal conductivity on solar cell temperature control characteristics is analyzed as shown in figure 4:

![Figure 4](image-url)

**Figure 4.** Characteristic diagram of influence of PCM thermal conductivity on solar cell temperature control. (a) T0=18°C, E=800W/m², (b) T0=18°C, E=900 W/m² and (c) T0=18°C, E=1000W/m².

It can be seen from figure 4 that for PCM thermal conductivity in the range of 0.3-1.3 W/(m·K), as the thermal conductivity increases, PCM thermal control effect on solar cell is continuously enhanced. For example, under irradiance of 800 W/m² and thermal conductivity of 0.3 W/(m·K), PCM can maintain the solar cell temperature below 57°C for 4427 s, and when the thermal conductivity is 1.3 W/(m·K), the duration when PCM maintains the solar cell temperature below 57°C is increased to 8970 s. However, as the PCM thermal conductivity is increased to 1.3 W/(m·K), thermal control performance of the solar cell deteriorates as the thermal conductivity increases. For example, under irradiance of 800 W/m² and thermal conductivity of 1.4 W/(m·K), PCM can maintain solar cell temperature below 57°C for 8372 s, but when the thermal conductivity is 1.6 W/(m·K), the duration when PCM maintains the solar cell temperature below 57°C is reduced to 8032 s. In addition, it can be concluded from the figure that the influence of PCM thermal conductivity on the thermal control characteristics of solar cells varies greatly under different solar irradiiances. For example, when irradiance is 800 W/m², 900 W/m², PCM has the best thermal control effect on solar cells under thermal conductivity of 1.3 W/(m·K), which can maintain the solar cell temperature below 57°C for 8970 s and 8144 s respectively. However, when irradiance is 1000 W/m², PCM has the best thermal control effect on the solar cell under thermal conductivity of 1.4 W/(m·K), and can maintain solar cell temperature below 57°C for 7238 s.

5. Conclusion

According to the structural model of PV/PCM system, the influence of different design parameters of PCM on the solar cell thermal control characteristics was studied. The results show that PCM thermophysical properties have obvious influence on solar cell thermal control characteristics. First, under the same conditions, for a lower PCM phase change temperature, solar cell thermal control effect is better. However, it is subject to the influence of ambient temperature and irradiance. For greater irradiance, the duration when solar cell temperature is maintained under control is shortened. Secondly, a greater PCM phase change enthalpy means better solar cell thermal control effect. PCM with the same phase change enthalpy has better solar cell thermal control effect when the irradiance is smaller. Thirdly, when PCM thermal conductivity is within a certain range of (0.3 W/(m·K)-1.3 W/(m·K)), as the PCM thermal conductivity increases, the solar cell thermal control effect is better. However, when the PCM thermal conductivity exceeds 1.4 W/(m·K), increase in thermal conductivity does not have significant effect in improving solar cell thermal control effect, and the thermal control effect of PCM thermal conductivity on solar cells is affected by solar irradiance.
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