Design and experimental study of thermal storage PV/T/PCM solar collector

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Abstract. In order to improve photoelectric thermal characteristics and practicability of PV/T collectors, a thermal storage PV/T/PCM solar collector was designed. Flexible copper indium gallium diselenide (CIGS) solar cells was applied in the collector to relieve the impact of operating temperature rise of the heat absorbing plate on the conversion efficiency of the solar cells, and solid phase change material was prepared to simplify integration process of the PV/T/PCM collector. In the meantime, PV/T/PCM solar collector system prototype was designed. The experimental results show ed that the temperature of the absorber plate and solar cells of PV/T/PCM system was reduced by 15° C and 20° C respectively compared with PV/T system, while thermal efficiency was increased by 21%. Meanwhile, in PV/T/PCM, the absorber plate had a lower temperature than the solar cells, which thus achieved the purpose of reducing the influence of the absorber plate on solar cells temperature. In addition, the solar cells output power of the PV/T/PCM collector system was increased by 6.7% compared to PV/T collector system.

1. Introduction

In 1978, Kern and Russell proposed the concept of photovoltaic/thermal (PV/T) solar system [1], which used air or water to cool solar cells and recycle the heat. Subsequently, extensive study has been conducted on structure optimization and energy transfer theory of PV/T collector [2-6]. Where, Aste et al established a simulation theoretical model of PV/T solar system and analyzed photoelectric/thermal characteristics of PV/T system. The results show that it has sound solar energy conversion and utilization characteristics [7]. Mojumder et al designed a single-channel PV/T air collector and studied its thermal and electrical efficiency. The results showed that the thermal efficiency was 56.19% and the electrical efficiency was 13.7% [8]. Huang et al made simulation analysis on PV/PCM system characteristics of phase change materials controlling solar cells temperature. The results show that PV/PCM system has the potential and advantages to improve solar cells output efficiency [9,10]. In addition, to recycle the heat stored in the PCM, the concept of PV/T/PCM was proposed [11]. Aelenei et al. performed a numerical analysis on building integrated PV/T/PCM solar system, and the results showed that integrating PCM in BIPV/T solar system was a potentially viable option [12]. However, research on PCM in PV/T system is still in its infancy, and intensive study is still needed in material properties of PCM, collector integration technology, cost and practicality [13]. In this paper, by analyzing problems existing in partially covered solar cells PV/T collectors, a heat storage PV/T/PCM solar air collector composed of flexible copper indium gallium diselenide (CIGS) cell, flat panel collector and solid phase change PCM is introduced. In the design, thermal contact resistance with flat
collector is reduced by flexible CIGS cell, and PV/T/PCM collector integration process is simplified with solid phase change material. In addition, photoelectric and thermal characteristics of the designed PV/T/PCM solar air collector system prototype and PV/T solar air collector system prototype were tested. The research results provide experimental basis for optimization design of PV/T/PCM solar collectors.

2. Characteristics of partially covered PV/T collector
For partially covered solar cells PV/T collector, the absorber plate not covered by solar cells is heated fast, which can improve collector practicality, but will cause solar cells operating temperature to rise and reduce solar cells output efficiency. For example, based on a 2 m² flat-plate solar collector, a PV/T collector with solar cells coverage of 0.59 was designed using a CIGS solar cells, and a PV/T solar air system test prototype was prepared, which consisted of PV/T controller, battery, air flower, bracket and related pipelines, TRT irradiance meter, Altai (USB2005) 32-channel data acquisition system, anemometer, TP100 temperature probe and temperature transmitter, etc. The test parameters mainly included PV/T collector air outlet temperature, air inlet temperature, absorber plate temperature, solar cells surface temperature, solar cells output voltage and current, wind speed, irradiance, etc. The schematic diagram of the system test is shown in figure 1.

![Figure 1. Schematic diagram of PV/T solar air collector test system.](image)

On January 9, 2018, the solar cells temperature, absorber plate temperature and air inlet and outlet temperature of the PV/T solar air collector system were tested in Chuxiong. During the test, the output air flow rate was 16 m/s, and the air outlet diameter was 24 mm. The test results are shown in figure 2.
It can be seen from the test results that for the designed PV/T solar air collector, the maximum operating temperature of the absorber plate and the solar cells reached 104°C and 108°C, respectively, the solar cells operating temperature reached above 80°C during the test period of 11:30-15:25, and absorber plate had a higher temperature than the solar cells of 8:13-11:50. It is mainly because in the partially covered solar cells PV/T collector, the absorber plate not covered by solar cells has a greater absorption of solar energy than solar cells. This shows that in the designed partially covered solar cells PV/T collector, the operating temperature of the solar cells is increased to some extent. Therefore, the key to improving practicality of PV/T collector partially covered by solar cells and improving solar energy utilization rate lies in how to regulate absorber plate temperature of PV/T collector.

3. Thermal storage PV/T/PCM collector design

The phase change material (PCM) is integrated on the partially covered solar cells PV/T collector to design the PV/T/PCM collector. The collector area is 2 m², the solar cells coverage is 0.59, and the distance between tube banks is 8 cm. The PV/T/PCM collector structure is schematically shown in figure 3, which consists of the CIGS solar cells, transparent cover, flat plate collector, phase change material (PCM), shell, insulation layer, etc.

In the PV/T/PCM collector, PCM phase change heat storage are used to control the absorber plate temperature and reduce the influence of absorber plate on the solar cells temperature; on the other hand, PCM stores the heat generated by the collector when the solar radiation is strong, which extends heat supply time of the collector and enhances its practicality.

CIGS flexible solar cells are selected for PV/T/PCM collector design. On the one hand, it lowers the junction surface thermal resistance with the absorber plate and improves the internal heat transfer characteristics. On the other hand, high operating temperature characteristics of CIGS flexible solar cells is used to weaken the effect of temperature increase on solar cells output efficiency. The CIGS
flexible solar cells technical parameters are shown in table 1.

| Parameter Name | Parameter Value | Parameter Name | Parameter Value |
|----------------|-----------------|----------------|-----------------|
| Length         | 1.7 m           | Voltage        | 18 V            |
| Width          | 0.37 m          | Power          | 70 W            |

In addition, considering the integrated packaging process and cost of PV/T/PCM collector, solid-solid phase change material is prepared, with its DSC characteristics and thermogravimetry (TG) characteristics shown in figure 4.

![DSC and TG characteristics of PCM](image1)

Figure 4. (a) DSC and (b) TG characteristics of PCM.

It can be seen from figure 4(a) that there are two endothermic peaks in DSC characteristics of the phase change material (PCM). Where, the first endothermic peak is a solid-solid phase change endothermic peak with an initial phase transition temperature of 77°C, the peak temperature is 92.20°C, and the enthalpy is 316.5 J/g; the second endothermic peak is a solid-liquid phase change endothermic peak with an initial phase transition temperature of 148.9°C, the peak temperature is 158.8°C, and the enthalpy is 166.9 J/g. The PCM has a large solid-solid phase change heat storage density and a phase transition temperature matched by PV/T collector temperature characteristics. Meanwhile, it can be seen from figure 4(b) that the PCM has good thermal stability during the solid-solid phase change process. Therefore, the prepared PCM is suitable for use in a PV/T collector. The integrated structure of the PCM phase change capsule and the collector is shown in figure 5.

![Structure diagram of thermal storage phase change collector](image2)

Figure 5. Structure diagram of thermal storage phase change collector. (a) PCM phase change capsule and (b) Internal structure diagram of collector.
4. Prototype design and testing
The PV/T/PCM solar air system prototype and PV/T solar air system prototype with the same structure were designed, and test system was constructed using Altai multi-channel data acquisition system. The test system mainly consists of Altai 32-channel data acquisition system, TRT radiation summary, anemometer, PT100 platinum resistance, temperature transmitter, etc., to achieve test of solar irradiance, ambient temperature, collector absorber plate temperature, solar cells temperature, inlet and outlet temperatures, phase change material temperature, solar cells output voltage and current during system prototype test. The test system photo is shown in figure 6.

Figure 6. Prototype test photo.

Figure 7. Solar irradiance.

Figure 8. PV/T/PCM prototype test characteristics. (a) Output electric power, (b) Absorber plate and solar cells temperature, (c) Absorber plate and cell temperature and (d) Prototype inlet, outlet air temperature.
In January 24, 2018, the prototype was tested in Chuxiong. During the test, the output air flow rate was 16 m/s, and the air outlet diameter was 24 mm. The test results shown in figures 7 and 8.

According to the test results, the collector outlet air velocity and the outlet pipe area, useful energy of prototype can be expressed as

$$Q_u = C_{air} \rho_{air} VS \left( T_{af} - T_{ai} \right)$$

(1)

where $C_{air}$ is the specific heat capacity of air (1.004 kJ.kg$^{-1}$. K$^{-1}$), $\rho$ is air density (1.29 kg.m$^{-3}$), $G$ is the flow rate of outlet air (unit: m$^3$/h), $T_{af}$ is outlet air temperature (unit: K), $T_{ai}$ is the inlet air temperature (unit: K), $V$ is the wind speed at the hot air outlet end (unit: m.s$^{-1}$), and $S$ is cross-sectional area (unit: m$^2$) inside the hot air header.

$$\eta = \frac{C_{air} \rho_{air} VS \left( T_{af} - T_{ai} \right)}{AE}$$

(2)

where $A$ is the total area of the collector array (unit: m$^2$), and $E$ is the solar irradiance (W.m$^{-2}$).

According to the test results, it can be seen that PCM exerts obvious temperature control effect on solar cells in the PV/T/PCM prototype as shown in figure 8(b), the maximum temperatures of absorber plate and solar cells are 81°C and 90°C, respectively. Compared with the maximum temperature of 105°C and 106°C of PV/T prototype absorber plate and solar cells as shown in figure 8(c), the temperature is reduced by 15°C and 20°C, respectively. According to equation (5), it is obtained from the test results that PV/T/PCM prototype has a daily heat efficiency of 45.9%, which is an increase of 21% compared with 38.2% of the PV/T prototype. In addition, CIGS solar cells have obviously increased output power by using the PCM. In the PV/T/PCM collector system, the output power increases compared to PV/T collector system owing to reduced operating temperature of the solar cells. As shown in the figure 8(a), its maximum output power and average output power are increased by 15 W and 4.7 W, respectively. Meanwhile, Heat supply time of PV/T/PCM collector system is prolonged as shown in the figure 7(d), indicating that heat storage characteristics of the phase change material can play a role in energy supply regulation to a certain extent.

5. Conclusion

Research on PV/T/PCM collector structure, materials and internal heat transfer storage mechanism was carried out. Secondly, a prototype of PV/T/PCM air collector system was prepared, and a comparative experimental study was carried out on PV/T air collector system with the same structure. The results showed that PCM exerted obvious temperature control effect on collector solar cells. Compared with PV/T collectors, temperature of absorber plate and solar cells of PV/T/PCM collectors are reduced by 15°C and 20°C, respectively, and the daily heat efficiency has increased by 21%. Meanwhile, in the PV/T/PCM, absorber plate has a lower temperature than solar cells, and the internal heat transfer characteristics are improved. In addition, solar cells output power is increased by temperature control. In the PV/T/PCM collector system, solar cells output power is increased by 6.7% compared to PV/T collector system. Meanwhile, heat supply time of the PV/T/PCM collector system is prolonged, which plays a role in energy regulation to a certain extent. In short, the designed PV/T/PCM collector has achieved the goal of improving efficiency and practicability.

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