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Experimental research on the performance of household-type photovoltaic–thermal system based on micro-heat-pipe array in Beijing

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ABSTRACT

This paper presented a novel method of dissipating solar photovoltaic heat based on the technology of micro-heat-pipe array and the utilization of photovoltaic-cell waste heat. This novel technology solved the problems of low PV electrical efficiency and thermal failure caused by high cell temperature, greatly increased the comprehensive utilization efficiency of solar energy, and extended the service life of photovoltaic modules. One-year experiments were conducted to investigate the electrical and thermal performance of a forced-circulation, household-type photovoltaic/thermal system based on micro-heat-pipe array in Beijing, China. Test results showed that on the four typical days in different seasons, the average electrical efficiencies were 13.76%, 11.92%, 13.71%, and 14.65%; the average thermal efficiencies were 31.62%, 33.07%, 24.99%, and 17.24%; and the average total efficiencies were 45.38%, 44.99%, 38.70%, 31.89%, respectively. The system met the demand of power supply on sunny days and the demand of hot water between March and November, except in cloudy days. These experimental results can provide basis and reference for practical applications of the system.

1. Introduction

The electricity conversion efficiency of a solar photovoltaic (PV) cell for commercial application is about 6–15%, whereas the rest of the radiant energy of the sun is absorbed by the solar cells and turned into heat. Without effective dissipation, excess heat leads to extreme cell working temperature as much as 50 °C above the ambient environment. With every 1 °C temperature increase, the relative efficiency of the crystalline silicon cell decreases by about 0.4% [1]. Except in winter, the temperature of PV cell may exceed 80 °C, which results in decreased efficiency by about 20%. The lifespan of a PV cell is also greatly diminished at high temperatures. Moreover, overheated spots caused by imperfections in cell material appear at high temperatures, resulting in problems such as failure of PV cell.

To overcome these problems, a solar PV heat dissipation and hybrid solar PV–thermal (PV/T) technology using water as the coolant has been developed. Currently, there are two major methods of PV/T technology: the sensible heat transfer of the coolant and the phase change heat transfer by heat pipe. For the first method, the main technology is to weld copper or aluminum tubes on the metal panels to realize the combination production of heat and power. This structure can be referred to as tube-and-sheet PV/T modules and numerous studies have been conducted for this PV/T technology by experimental and numerical analysis method. Huang et al. [2] measured the thermal performance of a tube-and-sheet PV/T solar system using the daily-efficiency test procedure. Results showed that the primary-energy conservation efficiency of the present system exceeds 0.60. Chow [3] developed an explicit dynamic model for a single-glazed flat-plate water-heating PV/T collector based on the controlled-volume finite-difference approach. The model was able to perform a complete energy analysis on the hybrid collector. Touafek et al. [4] also theoretically and experimentally studied a tube-and-sheet galvanized steel PV/T collector. Besides these, several studies were conducted to improve the performance of the PV/T system based on the tube-and-sheet concept. Zondag et al. [5] analyzed the thermal and electrical performance of nine different designs of PV/T collectors. Tripanagnostopoulos [6] studied several modifications for the bi-fluid PV/T solar collector to provide hot water or air depending on the season and the thermal needs of the building. Abu Bakar et al. [7] simulated the performance of the bi-fluid PV/T collector in the arrangement of the air channel

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and the serpentine-shaped copper pipe at different parameters. Ji et al. [8] proposed a novel design of tri-functional PV/T solar collector to avoid the freezing problem of water and meat seasonal demand of hot air. Liang et al. [9] tested the performance of the improved PV/T solar collector filled with graphite. Ibrahim et al. [10] analyzed the performance of spiral flow tube-and-sheet PV/T system. The factors affecting efficiency of the PV/T modules were also discussed [11]. However, this tube-and-sheet technology is affected by fin efficiency and tube–bonding quality; hence, the PV/T modules have the disadvantages of non-uniform temperature, low efficiency, poor reliability, complex production process and high cost. To improve the performance, Chow et al. [12] proposed that the tube-and-sheet design be replaced with a flat-box metallic thermal absorber to obtain highly effective heat transfer and durability. A numerical model of this PV/T collector was also developed [13] and the model was used to verify whether a glazed or unglazed collector system was more suitable for a specific application [14]. However, the problems of decreased efficiency caused by lower cooling ability of water to PV cell and heavy weight in running operation still exist. Many of these problems hinder the extensive application of PV/T technology by sensible heat transfer of water. Heat pipes possess application potential as PV heat dissipation technology given their various advantages, such as high thermal transfer ability, isothermal characteristic, and variable heat flux. Also some studies have been conducted for the heat-pipe PV/T technology. Pei et al. [15] proposed a heat-pipe PV/T system. The performances of this system were studied under different operating and structure parametric conditions by experiment and simulation. Moreover, the relationships of the overall thermal, electrical, and exergy efficiencies versus various parameters were discussed in detail [16]. Moradgholi et al. [17] investigated the performance of thermosiphon-type heat-pipe PV/T system with different working fluid in both spring and summer. Wu et al. [18] developed a theoretical model introducing the effectiveness number of transfer unit method to predict the overall thermoelectric conversion performances of the heat-pipe PV/T system. A detailed parametric investigation by varying relevant parameters was conducted based on the laws of thermodynamics. In these studies, PV heat dissipation and waste heat recovery technology are achieved by circular copper heat pipes, which increase the cost of PV/T technology. The contact surfaces of the heat pipe condenser section and evaporator section are extremely small, such that the thermal resistances increase and consequently degrade the heat transfer efficiency.

In summary, PV/T technology is still in the primary stage of investigation and exploiture. It still remains some distance away from being large-scale used because of limited commercial PV/T modules. The main reasons are as follows:

(1) The combination of circular water tubes or heat pipes and PV panels leads to larger contact thermal resistance and non-uniform temperature, which makes high PV temperature and lower electrical and thermal efficiency.
(2) The technology of combining water tubes or heat pipes and PV panels leads to poor reliability, complex production process and high cost.
(3) The conventional water-type PV/T module is not used in regions with cold climate because the freezing of water to ice can break up the module.
(4) The more recent studies of conventional water-type PV/T module has several vertical riser tubes, one dividing manifold and one combining manifold arranged in the configuration. Thus, the module has higher hydraulic resistance.

Therefore, a novel PV/T technology with reasonable structure and lower cost is expected. This study presents a novel method of dissipating solar-PV-cell heat based on micro-heat-pipe array (MHPA) and the utilization of PV-cell waste heat to overcome the disadvantages of the conventional PV/T technology, thereby introducing a novel water-cooled PV/T module based on MHPA (hereafter denoted as MHPA-PV/T module). The structure and character of the MHPA-PV/T module were introduced and the experiments were conducted on the household-type MHPA-PV/T system to test the electrical and thermal performance in Beijing, China. The test results were analyzed to provide information for the practical use of the MHPA-PV/T system.

2. MHPA-PV/T module

MHPA is a novel flat-plate heat pipe. Fig. 1 shows a flat aluminum plate with multiple parallel micro heat pipes operating independently within [19,20]. Each micro heat pipe has many inner microgrooves (or microfins) to enhance heat transfer by repeated evaporation and condensation of inner working fluid. The MHPA bears the advantages of high heat transfer performance, high reliability, high compressive strength, low cost, and small contact thermal resistance because of its special structure [21,22].

In this study, MHPA is used to cool the backboard temperature of PV cells and collect the PV-cell waste heat. As shown in Fig. 2, a novel water-cooled PV/T module called PV/T module based on MHPA (MHPA-PV/T) combines PV panel, MHPA, heat exchanger, and thermal insulation material. The upper surfaces of the MHPA are closely joined with PV-cell backboard by conductive silicone, and the MHPA condenser is also closely joined with heat exchanger by conductive silicone. The small slits between the MHPAs are used to absorb thermal expansion and thermal stress. When the MHPA-PV/T is in use, the MHPAs transfer the heat absorbed by the PV cell through the phase change of the working fluid in the MHPA to the circulating water.

The novel MHPA-PV/T module has the following advantages:

(1) The flat shape of the MHPA significantly increases the heat exchanger area compared with the conventional PV/T module, thus significantly improving the heat transfer capability.
(2) The MHPA-PV/T module is processed second based on the common PV panels and no welding is used in the processing, making the structure simple and fabrication easy.
(3) The MHPA contains a large number of independent micro heat pipes, thus improving the reliability of the PV/T module operation.
(4) The initial investment of the system for applying MHPA to reduce the cell temperature only increases about 20%. The cost of metal material is significantly lower than that of the conventional PV/T module.
(5) The MHPA uses low freezing points of the refrigerants, which makes the PV/T module suitable for extremely cold areas. The unique heat exchanger could exclude water easily, which could prevent the frozen cracking of the module during winter.
(6) There is only one smooth and straight cooling water tube with an inner diameter of 25 mm. Thus, the module has the small hydraulic resistance.

3. Experimental setup

To evaluate the performance of household-type MHPA-PV/T system in Beijing, China, the daily electrical and thermal performance for the MHPA-PV/T system was tested and analyzed.