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The experimental study of a two-stage photovoltaic thermal system based on solar trough concentration

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ABSTRACT

A two-stage photovoltaic thermal system based on solar trough concentration is proposed, in which the metal cavity heating stage is added on the basis of the PV/T stage, and thermal energy with higher temperature is output while electric energy is output. With the 1.8 m^2 mirror PV/T system, the characteristic parameters of the space solar cell under non-concentrating solar radiation and concentrating solar radiation are respectively tested experimentally, and the solar cell output characteristics at different opening widths of concentrating mirror of the PV/T stage under condensation are also tested experimentally. When the mirror opening width was 57 cm, the solar cell efficiency reached maximum value of 5.21%. The experimental platform of the two-stage photovoltaic thermal system was established, with a 1.8 m^2 mirror PV/T stage and a 15 m^2 mirror heating stage, or a 1.8 m^2 mirror PV/T stage and a 30 m^2 mirror heating stage. The results showed that with single cycle, the long metal cavity heating stage would bring lower thermal efficiency, but temperature rise of the working medium is higher, up to 12.06 °C with only single cycle. With 30 min closed multiple cycles, the temperature of the working medium in the water tank was 62.8 °C, with an increase of 28.7 °C, and thermal energy with higher temperature could be output.

1. Introduction

Energy is the material basis for the survival and development of human society. With the acceleration of economic development, increasing demand for energy and accelerated depletion of limited conventional energy, renewable energy development and utilization is of great significance. Solar energy resources are widely distributed and large radiation amount, its utility develops rapidly in recent years. However, the characteristics of low energy flux density, radiation with intermittent and uneven spatial distribution put forward a higher level of demand for the collection and utility of solar energy. Solar photovoltaic power generation converts solar radiation directly into electricity by using solar cells. Using concentrator technology can significantly improve energy flux density, improving the battery capacity per unit area, but at the same time, it will make the solar cell surface temperature rising, which will result in lower conversion efficiency. The heat energy transformed by the solar cell will be used recycle in the form hot water by using the cooling working substance pump circulation, which not only reduce the solar cell surface temperature and enhance the solar cell efficiency, but also might obtain the heat energy.

From the end of 1970's to the beginning of the 1980's, American Brown University's Russell, Arizona State University's Florschuetz and MIT Hendrie [1–4] use the working substance pump circulation to cool at the back of the solar cell to make the solar cell maintaining the low temperature work condition to recycle the heat energy. Later, the relevant basic theories, modeling analysis, structural optimization, as well as testing methods of PV/T system has caused researchers of the wide concern. Kalogirou [5] has established a solar PV/T system which can provide hot water and electricity for domestic, and simulate through TRNSY. Results indicate that PV/T system provides a considerable amount of thermal and electrical energy, and its economic viability is also increased. Chemisana [6] provides a concentrating photovoltaic thermal module for Fresnel linear concentrator, and verify the model of electrical and thermal behavior of the module through experiments. Daghigh [7] designed a new water-based PV/T collector for building-integrated applications, tested and evaluated its performance. Ammaar [8], in order to detect the optimal power operating point by considering PV/T model behavior, put forward a PV/T control algorithm based on artificial neural network. Calise [9] conducted the dynamic simulation for a high-temperature solar heating and cooling system based on concentrating photovoltaic

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thermal collectors. Karathanassis [10] designed with multi-objective by using a genetic algorithm for concentrating photovoltaic/thermal system. Gang [11] put forward a HP-PV/T system which could be well applied in cold region, and established the detailed simulation model. Buonomano [12] established a high-temperature PV/T system, and analyzed its thermal performance. Mishra [13,14] established a model adopting working medium of the solar PV/T system to continuously and circularly collect thermal energy, and made a comparative analysis of the system performance of the collector under the conditions that the cells are respectively partly covered and entirely covered. Ji [15] established a model of GaAs and super cell arrays based on trough concentrating photovoltaic thermal system, and tested the characteristic parameter. Renno [16] proposed a theoretical model of a solar PV/T system, and analyzed and evaluated the characteristics of its electric and heat energy while electricity, heat and cooling energy for household use are met. Touafek [17] put forward a new sheet and tubes hybrid PVT collector, and conducted the theoretical analysis and experimental research, results indicated that it had the better heat absorption and lower production cost when compared with other configurations of hybrids collectors. Li [18] established trough concentrator PV/T system, and tested the output performance of its solar arrays. Shan [19] established a dynamic model of outputting and utilizing hot water in buildings through the solar PV/T system, and the results showed that when there were fewer cell components in series, the lower the inlet temperature was, the greater the mass flow rate of the working medium was, and the greater the cell output efficiency was. Fang [20] proposed the situations of application of solar PV/T systems in China in recent years and pointed out the problems and solutions existing in the PV industry. In addition, studies on application of the solar PV/T system in the aspects of air heating and cooling were also conducted [21–26]. Li [27,28] realized a solar trough concentrating compound energy conversion. In terms of economic utility, Li considered that generation costs of the TCPV/T system could catch up with PV systems, and could output the extra heat energy during electricity generation. PV/T is currently used in industrial production and building applications [29–32], reflecting the economic value of comprehensive thermoelectricity utilization [33–34].

As far as the PV/T system, there is contradiction between maintaining the high efficiency electrical energy output and enhancing heat energy quality. The solar cell surface temperature could be maintained at 50 °C below by adjusting cooling working substance mass flow, and output the high efficiency electrical energy, but the heat energy quality was not high. Improving the quality of thermal energy obtained was of great significance to expand the use of solar energy range. In 2004, Australian National university Joseph [35] thought an important direction of the PV/T system development was that recycled the working substance to heat up the high temperature, so that it could be applied to a wide range of areas.

On the basis of the PV/T system, a metal cavity heating stage was added on the ‘two-stage photovoltaic thermal system based on solar trough concentration’ proposed herein, and was used for increasing the temperature of working medium after cooling down the solar cells, so as to effectively solve the contradiction between improvement of solar cell efficiency and increasing of heat energy temperature grade. Using 1.8 m^2 mirror PV/T system, the electrical output performances of the space solar cell at 5 cm away from the focal plane under different opening width of the mirror were tested. The experimental platform of the two-stage photovoltaic thermal system, 1.8 m^2 mirror PV/T stage and 15 m^2 mirror heating stage system as well as 1.8 m^2 mirror PV/T stage and 30 m^2 mirror heating stage system was established respectively, and both output characteristics under different conditions was tested, the results showed that the long metal cavity heating stage under single cycle have lower thermal efficiency, but temperature rise of the long metal cavity heating stage under a single circle is higher, can reach 12.06 °C.

2. System description

A two-stage photovoltaic thermal system based on solar trough concentration mainly consists of a PV/T stage, a metal cavity heating stage, a water tank, a water pump, wherein the PV/T stage comprises a solar trough concentrator, a PV/T stage cavity, a dual-axis tracking device; the metal cavity heating stage comprises a solar trough concentrator, a metal heating cavity, a one-dimensional tracking device. Fig. 1 is a schematic diagram of system structure. For the PV/T stage, the solar parabolic trough concentrator driven by the dual-axis tracking device can constantly track the sun. Solar radiation is converged on the PV/T stage cavity located at the focal line through the solar trough concentrator, so as to amplify the energy flux density on the solar cell surface. Meanwhile, heat on the cell surface is taken away by cooling working medium inside the PV/T stage cavity, so as to reduce solar cell surface temperature, to output electrical energy with high efficiency and get extra thermal energy. Then the working medium carrying heat is lead through the metal heating-stage cavity. By using the one-dimensional tracking device, solar radiation is converged on the metal heating-stage cavity positioned in the focal line through the solar trough concentrator, to heat the working medium in its inner cavity. Then the working medium is stored in the water tank and provides heat energy with certain temperature to the outside. The system adopts the water pump to drive the working medium in a forced cycle manner.

3. The influence of concentration on the electrical performance of solar cell

The length of the solar parabolic trough mirror adopted in the PV/T stage is 1.16 m, the opening width is 1.57 m, the geometric focal distance is 1.06 m, and the mirror optical efficiency is 0.7; the photoelectric sensing passive dual-axis tracking system with the tracking accuracy of 0.85 is used; and the solar cell output unit employed is a space solar cell array with crystalline-silicon as its substrate material, comprising 9 space solar cells connected in series with the specification of 71 mm × 62 mm, and the total length of the cavity is 80 cm.

3.1. Electrical performance of solar cell under non-concentration

Experimental studies on the performance characteristics of the space silicon solar cell array under non-concentration and concentration have been made respectively. Under non-concentration, *I–V* curves of the solar cells at different temperatures are shown in Fig. 2, the characteristic parameters are shown in Table 1.

Fill factor *FF* of the solar cell, solar cell efficiency η_{elec} under non-concentration, and solar cell efficiency η_{elecp} under concentration can be obtained through the formulae (1)–(3).

$$FF = \frac{P_m}{V_{oc}I_{sc}} \tag{1}$$

$$\eta_{elec} = \frac{P_m}{GA_{elec}} \tag{2}$$

$$\eta_{elecp} = \frac{P_m}{\mu A_a I_b} \tag{3}$$

where P_m indicates the maximum power of the solar cell; V_{oc} indicates the open-circuit voltage of the solar cell; I_{sc} indicates the short-circuit current of the solar cell; G indicates the total solar