HIGH-PERFORMANCE PV-T SUBSYSTEM PHOTOELECTRIC CONVERSION SOLAR CELL COUPLED THERMAL ENERGY STORAGE SYSTEM

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Abstract: Based on the traditional solar photovoltaic/thermal (PV/T) system, the experimental platform of compound parabolic collector (CPC) coupled PV/T system was constructed, and the measurement and control system (MCS) of the experimental platform was also proposed. According to the evaluation system of photothermal photovoltaic energy conversion performance, the change rule of photothermal power (PTP) of CPC coupled PV/T system was studied and analyzed when the inlet water temperature was 20°C and the ambient temperature was 28°C, as well as the change rule of thermal efficiency and photoelectric efficiency (PEE). When the solar radiation intensity reached 800W / m^2, the outlet water temperature of the system could reach more than 45°C under the condition that the power efficiency of the system was more than 10%, which could meet the demand of water and heating. The total amount of solar radiation in the whole day was 17.32MJ/m^2, the photoelectric output of CPC coupled PV/T system was 18.32MJ, the average PEE was 9.2%, the collector heat was 99.33MJ, the average photothermal efficiency was 50.1%, and the total efficiency of the system was 58.7%. In a word, compared with the traditional collector, the PV/T system proposed has better performance.

Keywords: PV/T system; CPC coupled PV / T system experimental platform; measurement and control system; photothermal

1. Introduction

As the energy development technology is improved, the research of alternative energy has always been a hot topic. In contrast with the traditional fossil energy, renewable energy is characterized by sustainability, renewability, and low pollution. Renewable energy, especially solar energy, has the highest utilization rate and wider application range [1]. At present, the application scope of solar energy can be divided into two categories. First, the solar heating system that converts solar energy into heat energy, such as the water heater using the sun. Second, the photovoltaic (PV) power generation (PG) system that converts solar energy into electric energy, such as the street lamp using solar energy [2]. Generally, these two types of systems are applied independently, but they can not fully utilize the converted solar energy when used alone, and they need additional power supply to the heating system to reduce the temperature of the system. Meanwhile, the PG efficiency of the PG system will also decrease with the increase of the temperature. To solve the above problems, some researchers combine PV modules with solar air / hot water collectors, namely PV / photothermal coupled collector (PV/T) system [3,4]. PV/T system can convert solar energy into electric energy and thermal energy simultaneously, with higher energy efficiency, and has the advantages of small volume and space occupation. PV/T has higher cost performance in comparison with the single solar energy conversion system [5,6]. In recent years, some researchers have developed a concentrating PV/T system by coupling the concentrating device with the PV/T system. This system can improve the absorption rate of solar energy and the thermal output power of the system by concentrating the sunlight on the energy receiving surface of the solar system. However, there are more researches on concentrated PV/T systems such as Fresnel, slot, and butterfly, but less on compound parabolic concentrator (CPC) PV/T systems [7].

Based on the traditional PV/T system, the experimental platform of CPC coupled PV/T system is constructed, and the measurement and control system (MCS) of the experimental platform is also put forward. In accordance with the evaluation system of photothermal PV energy conversion performance, the change rule of PTP and photoelectric power (PEP) of CPC coupled PV/T system is studied and analyzed when the inlet water temperature is 20°C and the ambient temperature is 28°C, as well as the change rule of PTP and PEP of CPC coupled PV/T system and thermal efficiency and PEE.

2. Method

2.1 PV/T collector

The system consists of back panel (TPT), PV glass, ethylene / vinyl acetate copolymer (EVA), aluminum alloy square tube channel, and polysilicon battery module [8]. The black TPT and PV glass are used to wrap the surface of polysilicon battery module. in addition, the black TPT is used for insulation of absorption plate and can improve the absorption of solar energy. And TPT has a certain viscosity, as well as excellent low permeability and weather resistance. Use EVE to bond TPT, PV glass, aluminum alloy square tube channel, and PV module. Considering the system situation and relevant documents, the aluminum alloy flat box pipe with relatively high cost performance is used [9]. The collector used is 1750mm in length, 200mm in width and 14.5mm in thickness.

2.2 CPC coupled PV/T experimental system

Fig. 1 shows the CPC coupled PV/T experimental system designed, which is composed of data tracking system, PV/T collector system, data acquisition system, and CPC concentrator. The system needs to ensure that the PEE is higher than 10%, and the total PE PT efficiency (PTE) is higher than 60%. It also needs to transfer enough heat for tap water to ensure that the domestic water consumption is between 40 and 50 degrees.

The specific idea of the system is: the tap water flows into the water tank for storage and the CPC coupled PV/T experimental platform. Through the booster pump when in use, the PV cell module is cooled by the flat box pipe, the temperature of the cooled tap water rises, and enters the incubator for storage, theyeby achieving the above-mentioned supply of 40 to 50°C warm water. The PE part of the system is connected to the battery and DC load through the PV controller with maximum power tracking (MPPT). The thermocouples are arranged at the upper, middle, and lower parts of each battery board of the system PT components. The staggered thermocouples are connected with the two ends of the heat transfer medium inlet and outlet, respectively, and all pipes are wrapped with insulation cotton. The electric regulating valve and driver are installed in front of the outlet water tank to realize the regulation of the tap water flow of the system. A solar radiation meter and a sunlight tracking device are installed in the middle part of the experimental platform to measure the solar radiation intensity and adjust the angle of the maximum solar radiation intensity. Meanwhile, the experimental platform can be controlled through the data acquisition module.

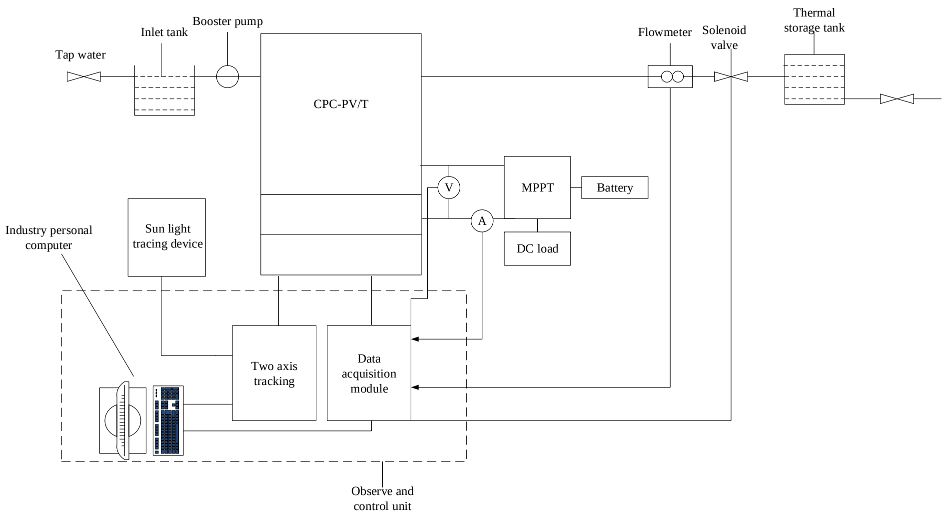


Figure 1 CPC coupled PV/T experimental system

2.3 Experimental MCS of CPC coupled PV/T system

The experimental MCS of CPC coupled PVT system consists of two parts: control system and test system. The test system is mainly used to collect various operation parameters of the experimental system, and recover, store and analyze the data. The control system is mainly used to adjust the operation parameters of the experimental system, thus realizing the regulation of the experimental system and discuss the experimental conditions under different working situations.

MCS mainly controls the flow of tap water entering the test-bed, so as to realize the high efficiency of PE conversion and the output of electric energy. As a negative feedback control, PID control is based on the adjustment and setting of P, I, and D parameters. It makes the control equipment act on the electric control valve and driver for controlling the water inflow of the system. The purpose is to ensure that the PEE of the CPC coupled PV/T collector experimental system is not less than 10%, and the outlet water temperature can reach the designed goal of 45°C.

Through the intelligent MCS, the parameters needed by the system can be obtained quickly and accurately. Based on the power calculation equation and PV PTE equation, the data measured by the intelligent calculation can be obtained efficiently. The specific calculation equation is:

The calculation of thermal power is $Q_1 = mc\left(T_1 - T_2\right)$, the calculation of PTE is $\eta_1 = \frac{Q_1}{CGS} = m\frac{c\left(T_1 - T_2\right)}{CGS}$, where m is the mass flow, T_1 is the outlet temperature, anad T_2 is the inlet temperature. The calculation of PEP is $Q_2 = IU$, the calculation of PEE is $\eta_2 = \frac{Q_2}{CGS} = \frac{IU}{CGS}$, wherein, I is the current value of the system, U is the voltage value of the system, C is the concentration ratio, G is the solar radiation intensity, and S is the area of the PV panel. The total efficiency of the system is $\eta = \eta_1 + \eta_2$.

2.4 Practical test of CPC coupled PV/T system

Due to the different use of water for daily life, the requirements of water temperature are also different, so the performance of the system is tested under different outlet water temperature. Through studying from the relevant literature and calculation simulation, this paper chooses to study and analyze the change rule of PTP and PEP of CPC coupled PV/T system, as well as the change rule of PTE and PEE with the decrease of solar radiation intensity when the inlet water temperature is 20°C and the ambient temperature is 28°C. The specific experimental steps are as follows:

The outlet water temperature is set at 45°C. The experimental system tracks the sun all day, and studies and analyzes the relationship between the solar radiation intensity and the PE and PT performance of the system;

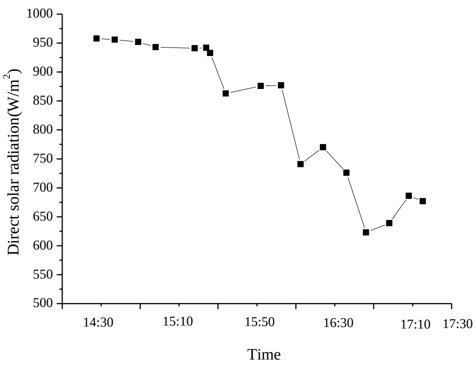
When the outlet water temperature is 40°C, 45°C, and 50°C, respectively, the experimental system tracks the sun throughout the day, and studies and analyzes the changes of PE and PT properties of the system.

In the process of the experiment, collect the experimental data from 10a.m. to 5p.m., conduct the experiment 20 minutes in advance, and collect the experimental data after the system is stable, thereby obtaining more accurate performance results of the experimental system. Additionally, clean the surface of CPC concentrator and PV module before each experiment, supplement the tap water in the inlet water tank, and discharge all the hot water in the incubator after the experiment.

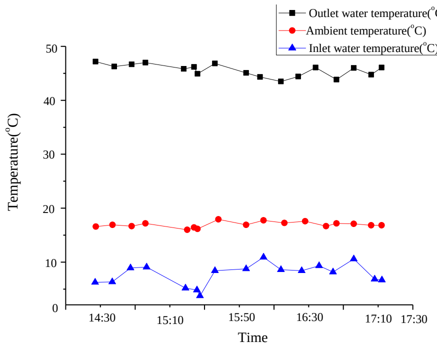
3. Results and discussion

3.1 Relationship between solar radiation intensity and performance of CPC coupled PV/T system

Fig. 2 shows the working environment parameters collected by the data acquisition system when the outlet water temperature of the response condition in MCS is set below 45°C, that is, the measured values of the ambient temperature and the inlet water temperature. It suggests that with the decrease of solar radiation intensity, the ambient temperature, inlet water temperature, and outlet water temperature are relatively stable, which are basically unchanged, so they are taken as fixed values.



(a)



(b)

Figure 2 The working environemnt parameters (a: solar radiation intensity; b: CPC coupling PV/T system ambient temperature, water inlet temperature, and water outlet temperature measurement value)

According to the above data, through MCS of the experimental platform, the relationship between the change of solar radiation intensity and the total efficiency of PE PT, electrical efficiency, and thermal efficiency of the system is obtained (Fig. 3).

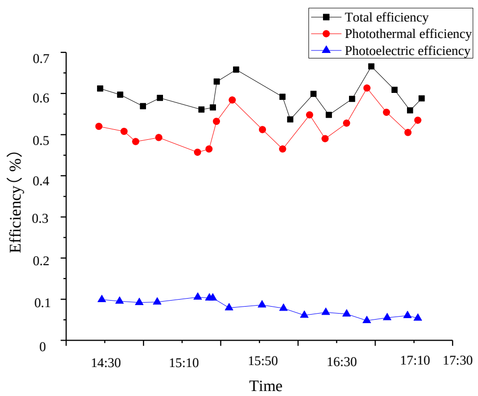


Figure 3 The relationship between the change of solar radiation intensity and the total efficiency, electrical efficiency, and thermal efficiency of the system

On the day of test, the temperature of tap water in the water tank at the inlet and outlet of the experimental system is 18°C and 45°C, respectively. The average temperature of the day is 28.1°C, and the maximum solar radiation intensity is maintained at about 955W/m^2. In the early stage of the experiment, considering the existence of response time, to avoid the sudden rise of PV panel temperature caused by the low flow of circulating tap water in the system and the serious damage of PV panel, the initial flow of tap water is adjusted to a constant value. The temperature of the tap water in PV/T will increase significantly after 18min, and when the outlet temperature is stable at about 40°C, the mode is adjusted to fix the outlet water temperature at 45°C. When the experiment is completed, the temperature of the incubator can be kept at 44.21°C, and the temperature rise in the whole day is 26.25°C. The results show that the PTE of the coupling system is 52.3%, the PEE is 9.3%, the heat collection is 6.12kJ/s, and the electric power is 1.11kW. The experimental data in Fig. 3 indicates that from 2:30 to 5:30 of the same day, with the gradual decrease of solar radiation intensity, PEE of the system also gradually decreases, but the PTE presents a fluctuating trend, and the overall change efficiency trend is close to PTE. From the above data, it can be concluded that the influence of solar radiation intensity on PEE is greater than that of PTE.

The relationship between electric power, thermal power, and total power and solar radiation intensity is shown in Fig. 4. Fig. 4 suggests that when the solar radiation intensity decreases gradually, the electric power and thermal power of the system also show a downward trend, and the downward trend is basically similar to that of the solar radiation intensity. The instantaneous peak output power of the system can reach 1.4kW, which meets the design requirements of 1kW experimental system. PTP is four times more than PEP, and with the change of the solar irradiation intensity, the change degree of PTP is greater than that of the thermal power. When the intensity of solar irradiation is decreased from 950W/m^2 to 680W/m^2, the electric power is decreased from 1050W to 423W, while the thermal power is decreased from 5810W to 4260W. The reason is that PV cells are more sensitive to solar radiation. When the solar radiation intensity is lower than 300W/m^2, especially when the scattering radiation is the main solar radiation, PV cells can no longer realize the conversion of solar energy to electric energy. Because of its structure, PV/T collector can absorb the solar energy on the surface of the system stably, and the change trend of PTE is small.

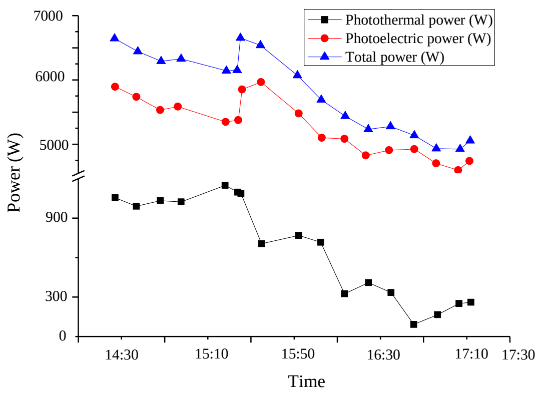


Figure 4 The relationship among electric power, thermal power, and total power and solar radiation intensity

3.2 Performance change of CPC coupled PV/T system with different outlet water temperature

To obtain the most suitable outlet water temperature of the system through experiments, a climate that is close to the outdoor temperature for eight days is selcted. The change rule of PEE, PTE, and total efficiency of the system is obtained when the inlet water temperature is mainted at about 20°C, the outdoor temperature is 28°C, and the outlet water temperature is 40°C, 45°C, and 50°C, respectively. As shown in Fig. 5, the change rule of PEE, PTE, and total efficiency of the system is obtained.

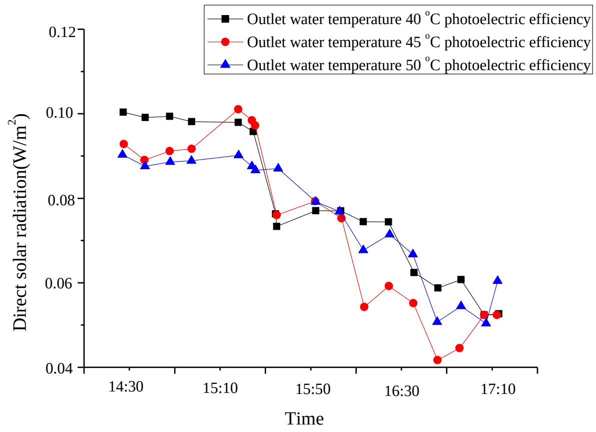


Figure 5 The change rule of PEE, PTE, and total efficiency

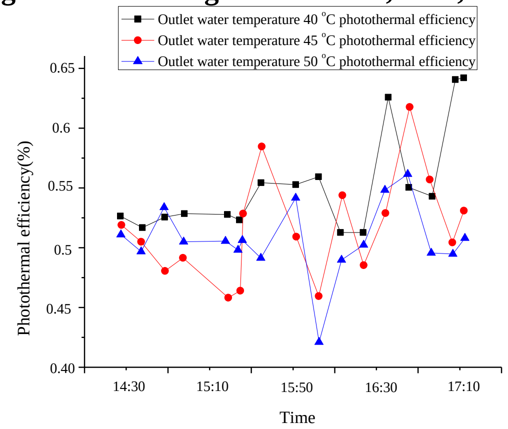


Figure 6 Variation of PTE at different outlet water temperature

According to Fig. 5, when the outlet water temperature is 40°C, the PEE of the system is higher than that of the system with outlet water temperature of 45°C and 50°C on the whole (has little difference on the system). The reason may be that the experimental data have some limitations due to the small variation of solar radiation intensity. Meanwhile, because the experimental system is a series connection of 12 battery plates, the temperature of each battery plate will change with the setting of different outlet water temperature. The empirical equation is $\eta_c = \eta_{ref}\left[1-\beta_{ref}\left(T_c - T_{ref}\right)\right]$ of efficiency and temperature, where T_{ref} represents the standard temperature, η_{ref} is the electrical efficiency under the standard temperature, β_{ref} is the temperature coefficient of PEE, and T_c represents the temperature of PV panels. It shows that the higher the temperature efficiency is, the smaller the change trend is, so the trend of 40°C is even greater.

Fig. 6 shows the change rule of PTE of the system under different outlet water temperature. It shows that the overall PTE will decrease with the increase of the outlet temperature. The lower the outlet water temperature is, the greater the mass flow of water is, and the more the heat collection capacity of the system will be, so the PTE will increase. However, the increase of this kind of collector heat is caused by more wasted heat. Therefore, in the future, the entropy efficiency evaluation system can be used as the judgment basis of PTE.

According to the above results, when the outlet water temperature is set to 40°C, the total efficiency of PE PT of the system will be significantly superior to that of 45°C and 50°C. The reason is that when the mass flow rate of the collector is high, it will take a lot of heat away from TPT of the battery, so that the working environment of the battery plate is closer to the standard situation. Hence, it can ensure that the PV/T system has high efficiency, the outlet water temperature should not be too high, and the lower the temperature is, the better the effect is. Considering that the temperature required for the actual domestic water can't be too low, the temperature of the hot water in the collector should also be weighed when the temperature of the hot water in the system is met, and the temperature of the outlet water should not be less than 45°C to ensure the needs of daily life.

3.3 All-day performance analysis of CPC coupled PV/T system

Set the outlet water temperature of the system to 45°C, PID parameter to P = 130, I = 1, D = 0.1, and get the all day test results of the CPC coupling PV/T system in Tab. 1. The experimental time of the system is from 10a.m. to 6p.m. A set of instantaneous performance data is measured every 30 minutes. At the beginning of the experiment, because the solar radiation intensity at 10a.m. has reached 889W/m^2, to avoid the sudden rise of the temperature of PV modules caused by the time response of automatic regulation, the fully open state of the valve is used at the beginning of the experiment. When the system is stable, it enters the automatic regulation mode. From 10a.m. to 12p.m., it can be seen that the sun's radiation intensity has declined twice because of the dark clouds. At the beginning of the system experiment, the solar radiation intensity is high, and it has good PE conversion efficiency. However, because the system is not stable, PTP and PTE are low, and PTE is only 37.9%. After two times of solar radiation intensity decreasing and rising, the system is still not completely stable, and can only operate in the fully-open valve. At 12p.m., it can be seen that the solar irradiance intensity drops sharply to 170W/m^2. However, due to the delay of heat transfer, the instantaneous thermal efficiency is more than 1. From 12:30p.m. to 4:30p.m., the solar radiation is in a high-intensity and stable state. In this case, the system can operate stably and is changed to the automatic adjustment operation mode, and the outlet water temperature is set as 45°C. Tab.1 shows that, in the steady state, the flow of the system is basically maintained at about 193L/h. PTP of the system can reach more than 1kW, and the PEE is about 10%. However, PTP is stable at about 6kW, and PTE is more than 50%. After 4:30 p.m., due to the decrease of solar radiation intensity, to maintain the outlet water temperature of 45°C, the water flow has decreased to 98L/h at 6 p.m. PEP and PEE are almost zero at 6 p.m. due to the decrease of irradiation intensity and the increase of the proportion of scattering irradiation.

Table 1 All-day performance analysis of CPC coupled PV/T system

Time	T_2	T_1	Discharge	Solar radiation intensity	Photoelectric power	Photothermal power	PEE %	Photothermal efficiency %
10:00	19.81	35.50	212	889	0.89	4.01	8.6	37.9
10:30	19.88	34.21	210	560	0.26	2.78	3.9	32.7
11:00	19.56	33.32	230	590	0.28	2.99	7.6	41.1
11:30	20.01	36.67	201	810	0.88	4.01	6.8	42.9
12:00	20.08	38.78	208	170	0.03	2.12	8.2	42.1
12:30	19.99	40.11	190	970	1.01	5.88	8.3	45.5
13:00	19.91	41.21	180	980	1.11	6.78	8.9	46.8
13:30	20.02	41.32	199	996	1.22	6.56	4.5	50.2
14:00	19.77	41.22	188	987	1.32	6.71	5.7	50.9
14:30	19.78	42.05	208	988	1.10	5.81	6.5	43.2

15:00	19.82	42.22	198	960	0.98	5.32	5.3	46.7
15:30	19.98	41.50	180	870	0.88	6.34	4.9	50.7
16:00	19.79	42.11	165	886	0.89	4.67	4.5	54.9
16:30	19.87	42.67	153	823	0.99	4.34	6.7	49.8
17:00	20.03	42.66	152	772	0.78	4.23	4.2	47.9
17:30	19.11	41.33	110	670	0.51	4.32	4.11	54.5
18:00	19.21	42.02	98	521	0.07	2.81	1.30	45.5

The total amount of solar radiation in the whole day is 17.32MJ/m^2, the PE output of CPC coupled PV/T system is 18.32MJ, the average PEE is 9.2%, the collector heat is 99.33MJ, and the average PT efficiency is 50.1%. The total efficiency of the system is 58.7% without considering the grade difference of thermal energy and electric energy. PEE is basically in line with the change of solar radiation intensity, and PEP of the module is almost zero when the radiation intensity is low, especially the direct radiation. Due to the hysteresis of heat transfer, the change of PTP and PT efficiency will not change with the change of solar radiation intensity. The change trend of PTP is similar to that of solar radiation intensity, and the PT efficiency is about 52%.

4. Conclusion

Based on the traditional PV/T system, the CPC coupled PV/T system experimental platform is constructed, and MCS of the experimental platform is put foward. Through the experiment, it is found that with the gradual decline of the solar radiation intensity, PEE of the system also gradually decreases, but the PT efficiency presents the trend of ups and downs. The overall change efficiency trend is close to the PT efficiency, so it is concluded that the solar radiation intensity has more influence on PEE than the PT efficiency. When the solar irradiance intensity gradually decreases, the electric power and thermal power of the system will also decline. The overall PT efficiency will decrease with the increase of the outlet temperature. Weighing the temperature of the hot water in the collector, the temperature of the outlet water should not be lower than 45°C. However, due to the impact of the environment, the analysis is not comprehensive enough. In the future work, the system operation of various weather conditions will be discussed.

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