A Study on the Characteristics of the Concentrated Solar Photovoltaic/thermal Integrated System

Dengxin Ai¹,²⁺, Guilin Wang¹,², Ye Li³, Zhiyong Gan¹,²

¹ Tianjin Electric Power Science & Research Institute, Tianjin, 300384, China
² Tianjin Key Laboratory of Internet of Things in Electricity, Tianjin, 300384, China
³ State Grid Tianjin Electric Power Company, Tianjin, 300010, China

⁺adx1991@163.com, ‡guilin602@163.com, †ibly@163.com, ‡tj_ganzhiyong@126.com

Abstract—This paper mainly introduces a comprehensive solar energy utilization system with low-CPC and polycrystalline silicon solar photovoltaic components. Outdoor experiments have been made to test the electrical efficiency, heat efficiency and their changes of the system with fixed temperature of outlet water and different sunshine conditions. Besides, this paper also compares the effects of outlet water at various temperatures on the efficiency of the whole system as well as the temperatures and flow rate responses with different PID parameters. Through analysis of these experimental data, the most desirable temperature of outlet water and PID parameters have been obtained in CPC-PV/T Hybrid Thermal-electric System, thus providing references for relevant experimental research.

1. Introduction
As a clean energy, solar energy is renewable and abundant everywhere in the world. The utilization of distributed photovoltaic solar energy could be an important way to achieve the “Dual Carbon” goal. It features local energy acquisition, decentralization and flexibility, and proximity to load centers, which is an important supplement to energy supply. Among distributed solar energy utilization technologies, the comprehensive utilization technology of Photovoltaic/thermal(PV/T) has gradually become a research hotspot in this field because of its high energy utilization rate, simultaneous output of electrical and thermal energy, and high suitability for building envelopes. This technology combines power generation with light and heat utilization, making full use of the energy of different solar energy spectrums. It can improve the photoelectric conversion efficiency of the panels by reducing the temperature of solar panels through cooling medium (When the temperature of solar panels rises by 1°C, the photoelectric conversion efficiency drops by 0.4%-0.6%). In addition to high-efficiency electric energy, it can also obtain domestic hot water at 50°C, which greatly improves the overall utilization efficiency of energy [1-4].

This paper presents a new type of CPC-PV/T integrated system. 8-day long experiment was conducted to study the heat conversion performance, analyze the influence of flow rate and outlet water temperature on the photoelectricity and heat conversion efficiency, and provide reference for the system’s structure parameters and flow rate selection.

2. Principles and structural design of the system

2.1. Principles of the system
As is shown in Fig.1, the concentrating solar PV/T integrated system studied in this paper can provides
45-50°C domestic heating water while ensuring electrical efficiency. Its working principles are as follows: firstly, water in the inlet water tank flows to the concentrated solar PV/T bench through the circulating water pump; then, it goes through the cooling channel on the back of the photovoltaic panel, taking away the heat of the solar panel; finally, it reaches the outlet water tank. The electromagnetic flowmeter in Fig.1 is used to monitor the flow value in actual operation. Advantech's industrial computer is applied to monitor the inlet temperature, battery panel’s temperature, and ambient wind speed, etc. It also adjusts the outlet water temperature and controls the solenoid valve to adjust the flow according to the demand. The system collects thermoelectric signals of the collector through Advantech's ADAM5000TCP module, edits the formula calculation on the industrial computer, and directly displays the required result in the interface.

2.2. Spotlight design
In this study, the photovoltaic panel is used as the receiver, therefore the width of the CPC is that of the photovoltaic panel. Polysilicon cells of 156 mm*156 mm are applied in this system, so the width of the CPC is set as 156 mm ($d_2$). This study chooses 4 as the concentration ratio. By eliminating the secondary reflection, it can be calculated that the height is 630 mm ($H_1$), and the incident light hole 624 mm ($d_1$), the best uniform surface to the exit light hole distance 29.2 mm ($FF_1$) and the untruncated lighting half angle is $10.6^\circ$ ($\theta$).

2.3. PV/T Components structure
Many researches have been done on PV/T modules at home and abroad, and lots of new ideas have been proposed from the cooling medium to the arrangement of the cooling runners. Considering the actual needs of this experiment, this system adopts a PV/T module with simple processing and high economic efficiency. The specific components are shown in Fig.2.
CPC concentrators, PV/T photovoltaic thermal components, data acquisition systems, tracking systems, etc. The data acquisition system uses Advantech's industrial computer and acquisition module to collect the inlet and outlet water temperature, each battery panel’s temperature, radiation intensity, wind speed, and flow rate. It also uses Danfoss driver and electric control valve to control the flow. The experimental parameters are displayed in Table 1:

| Symbol | Name                                | Value           |
|--------|-------------------------------------|-----------------|
| η_{ref}| Standard power efficiency          | 18.5%           |
| β_{ref}| Temperature Coefficient            | 0.004°C^{-1}    |
| t_{ref}| Standard temperature               | 20°C            |
| a      | Length of aluminum alloy square tube channel | 1.57m         |
| b      | Width of aluminum alloy square tube channel | 0.156m        |
| h      | Height of aluminum alloy square tube channel | 0.005m       |
| C      | Concentration ratio                | 4a             |
| FF     | Absorption factor                  | 0.83           |
| c      | Specific heat capacity of water     | 4.174 kJ/(kg·K) |
| δ_{Al} | Thickness of aluminum alloy square tube channel | 0.002m       |
| S      | The area of the photovoltaic panel  | 2.9 m²         |
| I      | Solar radiation intensity          | Provided by thermometer |

The CPC-PV/T part of the experimental system, which is mainly composed of CPC panels with low concentration ratio and PV/T photovoltaic thermal components. Water is used as the cooling medium, and the pipes are wrapped by thermal insulation cotton.

The measurement and control system can display the operating status of the system and the changes of various parameters. The change trend of photoelectricity, photothermal and total efficiency is displayed intuitively in the form of graphs. The electric power is obtained by the measured current and voltage of the system, and the efficiency is calculated by the formula.

4. Results and analysis

4.1. Performance changes in accordance with solar radiation intensity

Continuous experiments are conducted during a typical summer week. In order to meet the temperature requirements of domestic water, the outlet water temperature is set at 45°C. According to the experimental data, the ambient temperature maintains at 26°C and the inlet water temperature is 20°C. Under this circumstances, with the decrease of radiation intensity, this study explores the changing trend of flow, photoelectric power, photothermal power and the laws of photoelectric efficiency and photothermal efficiency of the system.

Fig. 3 illustrates the measured values of the relevant environmental parameters collected by the data acquisition module under the response-setting conditions. It can be seen that the parameters set with the irradiation: ambient temperature, inlet water temperature, and outlet water temperature have little change, which can be approximately regarded as fixed values.
As shown in Fig.4, it is obvious that both electrical power and heating power decrease with the decrease of the radiation intensity, whose trend are consistent with the radiation intensity. The peak value of the output electric power can reach 1kW. Obviously, the photothermal power is 4 times higher than the photoelectric power. As radiation intensity decreases, the change of electric power is more obvious than the change of thermal power. When the radiation intensity drops from 955 W/m² to 682 W/m², the electric power is reduced from 1040W to 428W. In contrast, the heating power is reduced from 5803W to 4251W.

4.2. PV/T system with different outlet water temperatures

In order to compare the best outlet water temperature, comparison experiment is carried out to obtain the change trend of photoelectricity, photothermal efficiency and total efficiency during 8 days of similar meteorological conditions. The inlet water temperature maintains 20°C and ambient temperature 26°C. The outlet water temperatures are respectively controlled at 40°C, 45°C and 50°C.

Fig.5(a) compares the photoelectric efficiency change curve at three different outlet water temperatures. It can be seen from that the photoelectric efficiency of the system at 40°C is better than 45°C and 50°C, but changes of the latter two are not obvious. This may be attributed to the fact that selected radiation intensity does not vary greatly, and that the experimental data has certain limitations. In addition, the test bench uses 12 panels arranged in series. When the outlet water temperature is different, the temperature of each panel is not consistent, neither is the efficiency of each panel. According to the empirical formula of efficiency and temperature, the higher the temperature is, the smaller the trend of efficiency change. Therefore, the changes at 40°C and 45°C are greater than those at 45°C and 50°C.
In the same way, the change trend of the photothermal efficiency of the system under these three outlet water temperature conditions is obtained. As is shown in Fig.5(b), the photothermal efficiency basically decreases as the outlet temperature increases. Because when the temperature is low, the flow is large and the energy grade is relatively low, the photothermal efficiency is high. In subsequent studies, the exergy efficiency will be used as the basis for judging photothermal efficiency.

4.3. Characteristics of PV/T system with different PID parameters

As for PV/T system, the hot water produced is for domestic use. In addition to improving efficiency, it is also necessary to consider the convenience of use and the smoother operation of the equipment during the adjustment process. This experimental system adopts PID controller and sets appropriate PID parameters according to the need to regulate.

After many experiments, it has been found that the P value is small, the flow rate will change greatly and the system will become very unstable due to the differential effect. Therefore, the P value should be large and its parameter range is 50–150. When I is 1, and D 0.1, the system is relatively stable. In the experiment, three PID parameters P=70, I=1, D=0.1; P=100, I=1, D=0.1; P=130, I=1, D=0.1 are chosen to observe. Its flow rate, outlet water temperature and electric heating performance parameters are shown in Fig.6 as (a), (b), (c), respectively.

![Outlet water temperature and flow changes when P=70](image)

(a) Outlet water temperature and flow changes when P=70

![Outlet water temperature and flow changes when P=100](image)

(b) Outlet water temperature and flow changes when P=100

![Outlet water temperature and flow changes when P=130](image)

(c) Outlet water temperature and flow changes when P=130

**Fig.6 Outlet water temperature and flow changes with the change of PID parameters**

In the three cases, the outlet water temperature is set at 45°C, and the radiation intensity is 900W/m². It can be seen that when the parameter group P=70 is selected, the flow rate changes quickly, reaching the set value in only 14 minutes, but the temperature continues to rise, reaching a maximum of 48°C, and the flow rate dropping to 140L/h. It takes 37 minutes to finally reach the set value after the fluctuation. The fluctuation is too severe, which is unreliable for the stability of the
system and the safety of the pipeline. When the parameter $P$ is selected as 100 and 130, it enjoys better stability. The parameter group of $P=100$ also has an unstable temperature drop, but the oscillation amplitude is small and does not damage the system. It takes about 36 minutes to reach the set temperature. The temperature rise of the parameter group with $P=130$ is relatively gentle with minor fluctuation, which takes about 36 minutes. In comparison, the temperature change is more stable with $P=130$, and over-temperature phenomenon doesn’t occurs. Therefore, in the actual system operation, $P=130$ is selected as the operating parameter.

5. Conclusion
This article describes the experimental platform and related parameters of the low-CPC concentrating solar PV/T system from the perspective of engineering practice. The related results of the experiment are summarized as follows:

1. The 1kW concentrating solar PV/T system can ensure that the outlet water temperature of the system can reach 51°C. It can fully meet the needs of domestic water and heating.
2. When other parameters are constant, the electrical efficiency and thermal efficiency decrease as outlet water temperature increase. Therefore, in the actual application, outlet water temperature should be set at the lowest point as required. In this way, it not only meets the needs of the project, but also attains the highest efficiency.
3. When using PID automatic adjustment, whether in flow adjustment mode or temperature adjustment mode, there is a certain hysteresis, which will cause sudden changes in valve adjustment and sharp increase in pipeline pressure. In order to ensure the service life of the system, a particularly sensitive adjustment method should not be used, and appropriate PID parameters should be selected.

Acknowledgments
This work was supported by “Science and Technology Project of State Grid Tianjin Electric Power Company (KJ21-1-19 Research on Key Technologies of Distributed Solar Cogeneration Integrated Energy System)”.

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