Performance Analysis of Compound Parabolic Concentration Photothermal and Photoelectricity Device for Soil Heating in Facility Agriculture

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Abstract

It is difficult for solanum crops to grow continuously during winter in severe cold regions. Thus, a soil heating system for facility agriculture based on solar concentration technology was proposed, and a novel compound parabolic concentration photothermal and photoelectricity device (CTPV) equipped in the system was designed to address this problem. In accordance with the structure of the device, LightTools optical software was selected to analyze the variation trend of the light escape rate of the device with the different incident angles. On the basis of the calculation results, an experimental test system was used to investigate the relationship of the air temperature of the inlet and the outlet, total output power of the solar cells, and photothermal and photoelectricity efficiency of the device with the operation time during a sunny day. Research results reveal that the light escape rate of the device is 5.36% at an incidence angle of 12°. At a velocity of 1.5 m/s, the maximum air temperature of the outlet can reach 55.6 °C, and the total output power of the solar cells is 474.4 W. The variation of the total power of the solar cells is consistent with the simulation results. The maximum instantaneous heat collection and the maximum photothermal and photoelectricity efficiency of the device are 306 W and 60.4%, respectively, and the average efficiency is 44.9%. This study can serve as a reference for compound parabolic concentration technology applied for soil heating in facility agricultural soil heating systems.

Keywords Facility agriculture · Photothermal and photoelectricity · Concentration · Soil · Heating

Introduction

Facility agriculture is a modern mode of agriculture that can carry out seasonal vegetable and fruit production and improve output under artificially created climate conditions [1–4]. Conventional agricultural heating systems result in carbon emission and environmental pollution, and high planting costs [5]. Therefore, a series of agricultural heating technologies has been studied. These technologies integrate

abundant solar energy resources in the facility agricultural planting region.

Song et al. [6] designed a solar air collection and heat release system used in a green house and analyzed the influence factors on the instantaneous heat collection and heat collection efficiency of the system. The results indicated that at a velocity of 2 m/s, the maximum heat collection efficiency and instantaneous heat collection of the system were 67.7% and 494.4 W/m², respectively. Chen et al. [7] combined the multi-curved surface concentrating structure air collector with the phase change heat storage ventilation wall used in greenhouses. They found that compared with a single collector tube concentrator, the airflow of dual collector tube concentrator increased by 100%, the heat collection per unit are increased by 16%, and the heat collection efficiency increased by 9%. Han et al. [8] analyzed the heat transfer process of a greenhouse using solar multi-surface air collectors with double-receiver tubes and used a mathematical model to verify the process with an actual greenhouse system. Their test results revealed that whether the outside

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of the reflector was attached to the insulation layer or not, the average relative error was 3.7%. Zhu et al. [9] designed a plate-type compound parabolic concentrator that can be used for a facility agricultural heating system, which adopted a novel straight-through metal–glass sealed vacuum solar collector tube. The test data showed that the maximum efficiency of the collector was 65.4%.

Both the instantaneous heat collection and heat collection efficiency of the solar air collector system change greatly with time. Thus, a solar collection system combined with high-efficiency photovoltaic technology [10] to improve the total output energy and conversion efficiency has become a research priority [11–14]. Yang et al. [15] presented a novel low-concentration photovoltaic/thermal solar-assisted water source heat pump. The experiment showed that the maximum electrical efficiency was 15.2%, with the maximum thermal efficiency being 86.7%. Mahdavi et al. [16] studied a facility agricultural test system powered by solar photovoltaic/thermal collectors. The theoretical and experimental results presented a relatively high coefficient of correlation, around 95%. Evangelos and Axaopoulos [17] explored the performance evaluation standard of solar-assisted ground source heat pump systems powered by photovoltaic-thermal collectors. They concluded that the renewable energy power proportion can indicate the overall energy performance of the systems.

In accordance with the planting requirements for the soil temperature of facility agriculture in winter and the investment cost of the heating system, the total output energy heat collection per unit area of a non-tracking compound parabolic concentrator (CPC) system needs to be improved. On the basis of previous research, a novel agricultural soil heating system is proposed. This system has double-sided solar cells connected by two groups of silicon-based solar panels that are attached to the light inlet of the traditional CPC. The

solar energy utilization efficiency of unit collector area is increased through photothermal and photoelectric coupling utilization of the incident sunlight. Furthermore, the relationship between the incident angle and the light escape rate of the device is calculated theoretically. The variation laws of the air temperature rise of the receiver and the total photothermal and photoelectricity efficiency during the operation time are studied. This study can provide a reference for the application of distributed solar energy facility agricultural soil heating systems.

Soil Heating System for Facility Agriculture Based on Solar Concentration Technology

In severely cold and cold areas, the soil temperature is too low to meet the growing need of solanum crops. Although the soil temperature can be effectively improved by applying solar heating measures, farmers will be discouraged by the high investment and maintenance costs. In addition, the popularization of traditional solar agricultural heating technologies is limited by the low solar energy density, short sunshine time, and poor heating capacity on cloudy and snowy days. Therefore, they are strongly dependent on auxiliary heating facilities in winter.

A novel agricultural soil heating system based on solar concentration technology is presented in this paper. The system structure is shown in Fig. 1. The solar concentrating system was composed of several compound parabolic concentration photothermal and photoelectricity devices (CTPVs) in series and was built on the ground south of the facility agriculture location. A single-layer glass tube embedded with a *-shaped receiver, whose surface was sprayed with dark light-absorbing material, was placed at the focal spot of the CTPV. The shape of the *-shaped receiver

Fig. 1 Diagram of facility agricultural soil heating system based on compound parabolic concentration and heat collection

is similar to the Chinese character meter. The tube was filled with air, which was circulated as the heat exchange medium. It flowed in the single-layer glass tube and exchanged heat with the receiver driven by a draft fan. Then, the air was heated, flowed into a heat exchange pipe buried in the soil, and then exchanged heat with the soil outside the pipe to increase the planting soil temperature for facility agriculture. The air returned to the solar concentrating system after heat exchange and had a decrease in temperature. The incident sunlight, which was not absorbed by the $\ast$ -shaped receiver, was received by the solar cells and converted into electricity to drive the draft fan used in the soil heating system.

Compared with the traditional solar heating system, the proposed novel heating system has the following characteristics: (1) The compound parabolic concentrator (CPC) can be placed and operated in a fixed manner, thus having low requirements for power and other infrastructure. At the same time, it can integrate easily with the facility agriculture, has little impact on the reception of sunlight by the crops, and has lower operation and maintenance costs in the later stage. (2) Air is chosen as the heat transfer medium, which has low heat transfer resistance and can directly transfer heat to the soil. In winter, engineering requirements such as antifreeze, leakage, and rehydration industrialization convenient. (3) Soil is used as the warming medium for the system. It can not only supply energy for crop growth but also has the function of heat storage. In addition, the adverse impact of insufficient sunshine on facility agriculture on cloudy and snowy days can be alleviated.

Compound Parabolic Concentration Photothermal and Photoelectricity Device and its Optical Characteristics

The solar energy capture and conversion device is the key component and driving source of the facility agricultural soil heating system. On the basis of the previous analysis, a novel CTPV is designed in this study. Apart from having the advantages of low requirements for sun tracking accuracy, replaceable receiver, internal concentrating, and receivable partial scattered light, it also has the characteristics of photothermal and photoelectricity efficient coupling, a large total energy output heat collection per unit area, and a realizable self-powered operation distributed system.

Compound Parabolic Concentration Photothermal and Photoelectricity Device

The CTPV was composed of a CPC, a glass cover plate, a single-layer glass tube, a $\ast$ -shaped receiver, and a double-sided solar cell embedded on the lower side of the glass cover plate. A photograph of a real CTPV device is shown in Fig. 2,

Fig. 2 Photograph of a real CTPV device

Fig. 3 Sectional dimension diagram of the CTPV. $\ast$ AC is the sunlight inlet; AB and CD are parabolic reflectors; BE and DF are plane mirrors; EOF is the bottom parabolic reflector

and its section size and normal incident light transmission and aggregation are shown in Fig. 3. The $\ast$ -shaped receiver was welded by six stainless steel sheets with selective absorption coating sprayed on the surface, embedded in a single-layer glass tube to form a light-heat conversion component, and was fixed at the focal spot of the concentrator. The air was heated when it flowed through the surface of the $\ast$ -shaped receiver. In addition, the incident light receiving and photothermal conversion of the concentrator would not be influenced when the sunlight was normally incident, because the lower edge points of the two groups of solar cells opposite to the back of the glass cover plate intersected with the light reflected by the upper edge points of the concentrator. However, the light that escaped from the device could be partially received by the solar cells to generate electricity when the sunlight incident angle increased.

Optical Characteristics of Compound Parabolic Concentration Photothermal and Photoelectric Device

The variation trend of sunlight incident angle increases at first and then decreases when the CTPV has a fixed placement to ensure the normal incidence of sunlight at noon. Thus, the height of incident light deviating from the Y -axis is defined as the incident angle, which corresponds to the solar altitude of the east–west placement device in practical application. As shown in Fig. 3, the light escape rate is defined as the ratio of the number of light rays escaping from the device after multiple reflections in the device to the number of light rays entering the inlet of the device. Its value can be used to measure the ability of the device to receive incident light, and the calculation formula is as follows:

$$\eta_e(\alpha) = \frac{N_e(\alpha)}{N(0)} = 1 - \frac{N(\alpha)}{N(0)} \quad (1)$$

where η_e is the light escape rate of the device; $N_e(\alpha)$ is the amount of sunlight escaping from the sunlight inlet of the device when the incident angle is α ; and $N(0)$ is amount of sunlight received on the surface of glass cover plate when the incident angle is 0° .

The three-dimensional model of CTPV was established in SolidWorks software and imported into LightTools software. The dimension of the surface light source was consistent with the sunlight inlet of the device, and the incident sunlight was an equidistant parallel beam. Each reflecting surface of the device was a specular reflection. Both the surface of the * $\ast$ -shaped receiver in the single-layer glass tube and the outer surface of the double-sided solar cells were the sunlight receiving surface of the device.

The constructed facility agriculture soil heating system is located in Hohhot, Inner Mongolia Autonomous Region ($N40^\circ 50'$, $E111^\circ 42'$). Thus, the operation time of the solar concentrating system is from the autumn equinox of the current year to the spring equinox of the next year, during which the variation range of solar altitude is 25.7° – 48.3° . The corresponding variation range of the incident angle is from 0° to 12° because of the symmetry and fixed placement of the CTPV. The light escape rate of CTPV is calculated and compared with that of the traditional CPC [18], which has the same size parameters shown in Fig. 4, to investigate the improvement effect of CTPV on the receiving capacity of the incident light.

The light escape rate of the CTPV has the same trend as the CPC, increasing with the incident angle shown in Fig. 4, but the CTPV has a lower light escape rate. When sunlight is normally incident ($\alpha=0^\circ$), the light escape rate of the CTPV is the same as that of the CPC; that is, the additional two groups of double-sided solar cells have little effect on the performance of

Fig. 4 Effect of incident angle on the light escape rate of the concentrator

Fig. 5 Diagram of ray tracing when the incident angle is 12°

the CPC to receive normal incident light. As the incident angle increases to 12° , the light escape rate of the CPC is 40.5%, and the light escape rate of the CTPV is 5.4% which is 86.8% lower than that of the CPC. This result shows that compared with the CPC, the increase in the incident angle does not affect the light escape rate of the CTPV. Most of the incident light can be received and converted into heat, and the rest of the incident

light is received and converted into electricity by solar cells. The escaping light is received by the front and back of the right double-sided solar cells presented in Fig. 5.

Performance Test and Analysis of Compound Parabolic Concentration Photothermal and Photoelectricity Device

Performance Test System

A performance test system of CTPV was established based on the results of the above optical calculation analysis. The factors that affect the performance of the device were obtained by exploring the changes of inlet air temperature and outlet, instantaneous heat collection, output power, and total efficiency of CTPV with operation time under actual weather conditions.

The installation angle of the CTPV could be adjusted, with the light window set on both terminal faces to collect and utilize the lateral incident light. The frame of the device was made of stainless steel, and the reflective surface was made of a reflective aluminum plate with a reflectivity of 0.85 and a length of 1 m. Other dimensions are presented in Fig. 3. The basic dimensions of a single-layer glass tube were the inner diameter of 0.11 m, a length of 1.2 m, and a thickness of 2.8 mm. The thermal conductivity of the single-layer glass tube is 0.76 W/(m·K). The projected height of the **shaped receiver* was similar to the diameter of a

single-layer glass tube and had a length of 1 m. The material of the pipe is PVC plastic.

The structure of the device performance test system is displayed in Fig. 6. Under actual weather conditions, real-time data acquisition was performed for solar irradiance, ambient temperature, inlet air temperature and outlet of the CTPV, instantaneous heat collection, and solar cell output power. Multiple K-type thermocouples were arranged at the inlet and outlet of the single-layer glass tube to ensure accurate temperature changes after heat exchange between the circulating air and the **shaped receiver*, and the average value was taken as the inlet air temperature and outlet. The temperature was recorded by a multi-channel data recorder. Solar irradiance and ambient wind speed were obtained by a handheld solar meteorological workstation (YGSC-1, Jinzhou Sunshine Meteorological Technology Co., Ltd., Jinzhou, China). Air velocity and its temperature were measured by a hotwire anemometer (TES-1340, Taishi Electronic Industry Co., Ltd., Taiwan, China), with an accuracy of 0.01 m/s. The solar energy density of the receiver was collected and verified by a heat flux meter (HFM-201, Kyoto Electronics Company, Japan). The output power of the double-sided solar cells was measured by a solar power monitoring system (TRM-FD1, Jinzhou Sunshine Meteorological Technology Co., Ltd., Jinzhou, China). The test accuracy of the K-type thermocouples was $\pm 0.5^\circ\text{C}$.

Fig. 6 Schematic of the performance test system

On the basis of the first law of thermodynamics, the photothermal and photoelectricity efficiency η of the device was calculated according to Eq. (2)

$$\eta = \frac{\int_{t_1}^{t_2} q_w dt + \int_{t_1}^{t_2} p dt}{\int_{t_1}^{t_2} I_{sun} A_c dt} \quad (2)$$

where I_{sun} is the solar irradiance received by the sunlight inlet (W/m^2); A_c is the sunlight inlet area (m^2); p is the output power (W); and q_w is the instantaneous heat collection (W), which can be calculated by Eq. (3)

$$q_w = \frac{\pi}{4} d^2 \rho v c_p (T_{out} - T_{in}) \quad (3)$$

where ρ is the density of the heat exchange air (kg/m^3); v is the air circulation velocity (m/s); c_p is the specific heat capacity of heat exchange air at operating temperature ($\text{J/(kg}\cdot\text{K)}$); and T_{in} and T_{out} are the air temperature at the inlet and outlet of the receiver (K), respectively.

To improve the test accuracy, the solar power monitoring system, handheld solar meteorological workstation, hot wire anemometer, heat flux meter, and K-type thermocouples used in the test were all checked. Experiments were conducted from August 26 to September 2, 2020. The airflow rate was maintained at 1.5 m/s by the control system.

Influence of Operating Conditions on the Photothermal and Photoelectricity Output of the Device

In accordance with the simulation results of optical characteristics of the CTPV, the operation time was 10:00 am–14:00 pm, during which the variation range of solar altitude was close to the optical calculating range. The

Fig. 7 Curve of solar irradiance and ambient temperature on test day

Fig. 8 Change of air temperature at inlet and outlet

measurement periods were characterized by clear days with excellent air quality. The CTPV was mounted from east to west at an installation angle of 60° to guarantee that sunlight was normal incident into the device at noon. Figure 7 shows the variation in solar irradiance and ambient temperature during the experiment. Figure 8 presents the variation curve with solar irradiance of air temperature at the inlet and outlet of the device.

The solar irradiance increased first and then decreased during the operation time, and the ambient temperature was generally maintained at about 26°C , as illustrated in Fig. 7. At noon, the solar irradiance was about 730 W/m^2 , and the area of the sunlight inlet of the device was 0.7 m^2 . At this time, the solar energy received by the device was about 510 W.

The variation tendency of the inlet air temperature of CTPV is consistent with the ambient temperature, and the outlet air temperature has a similar change trend with the solar irradiance. When the solar irradiance is stronger, the temperature of the output air will be higher (Fig. 8). The air temperature at the outlet and the temperature rise of the device reached the maximum of 55.6°C and 23.7°C , respectively, at 12:00. With the decrease in the solar irradiance and the increase in the incident angle, the air temperature difference at the inlet and outlet of the device decreased to 11.6°C . The variation curve of instantaneous solar thermal energy of the device during operation time calculated by Eq. (3) is shown in Fig. 9.

As shown in Fig. 9, the instantaneous heat collection of the CTPV reached the maximum at 12:00, with a value of 306 W, and then decreased with the reduction of solar irradiance. The main reason is that the inlet air temperature of the device is close to the ambient temperature and

Fig. 9 Change in instantaneous heat collection

changes minimally, while the change of outlet air temperature is mainly affected by solar irradiance and sunlight incidence angle. With the change in the temperature difference between the inlet and outlet of the device being consistent with the change of solar irradiance, the instantaneous heat collection energy of the device increases first and then decreases.

As a result, the sunlight entering the CTPV that is not received by the receiver can be received by the solar cell and converted into electricity. This condition can not only realize the automatic switching of photothermal and photoelectricity conversion in the same device but can also solve the technology bottleneck of the non-tracking CPC being unable to effectively receive oblique incident sunlight [19, 20]. In the experiment, two groups of symmetrical four amorphous silicon solar panels were arranged under the glass cover plate

Fig. 10 Variation of the output power of the device

of the sunlight inlet of the device, in which the back of two solar panels was opposite to each other to form a double-sided solar cell. The sum of the electric power output of the four solar panels was the total output power of the device. A sliding wire rheostat was used as the electric load to conduct a real-time test of the change in the output power of the solar cells with the operation time, as shown in Fig. 10.

Figure 10 shows that the output power of the device is symmetrically distributed with the change of operation time. The output power is the minimum at 12:00 and reaches the maximum in the two periods of 11:00–11:45 and 12:15–13:00. The main reason for this condition is that the output power of solar cells is related to solar irradiance and the amount of sunlight received by the solar cells. When the solar irradiance is the maximum and the sunlight is normally incident, the majority of the sunlight entering the device is converted into thermal energy output by the receiver, and only part of the scattered light is received and converted into electricity by the solar cells. In the two periods adjacent to noon, the sunlight is mainly oblique incident. Thus, the proportion received by solar cells and the total output power increase. Although oblique incident sunlight was received by solar cells during the start and end of the test, the solar irradiance is too low to produce high total output power. This finding is consistent with the analysis results on the optical characteristics of the device.

Analysis of Total Efficiency of Photothermal and Photoelectricity of the Device

Although thermal energy is the main output of the CTPV, the incident sunlight that is not received by the receiver can be received by the solar cells and converted into electricity. Therefore, the power can be supplied to the draft fan used

Fig. 11 Change in total photothermal and photoelectricity efficiency of the device

in the soil heating system. When the fixed CTPV is not used during summer, the sunlight enters the device at a large incident angle because of the large solar altitude angle at noon. Therefore, the receiver embedded in the single-layer glass tube can be protected against overheating, thus prolonging the service life of the device. Figure 11 depicts the variation trend of the photothermal and photoelectricity efficiency of the device during operation time as calculated by Eq. (2).

The trend of the photothermal and photoelectricity efficiency of the device is presented in Fig. 11. At 12:00, the total efficiency reaches its highest value of 60.4%. The average total efficiency of the device is 44.9% during the test period. The factors that affect the photothermal and photoelectricity efficiency of the device are solar irradiance, the air temperature difference between inlet and outlet, and the output power of solar cells. Notably, the CPC is a type of internal condensing device, which will form the greenhouse effect during operation. This condition is due to two main reasons. First, the heat dissipation loss between the receiver and the environment is reduced. Therefore, the expensive glass vacuum tube can be replaced by a cheap and easily available single-layer glass tube. Second, the temperature rise in the cavity of the device will also affect the photoelectric conversion capacity of the solar cells. In general, the design of the device is beneficial to the CPC in some aspects, such as the improvement of the total output energy and total efficiency in heat collection per unit area and the reduction of the investment cost of the non-tracking solar concentrator device.

Conclusions

In this study, a novel CTPV was designed, and its structure and operation principles were introduced. The LightTools software was used to conduct theoretical research on the change in the light escape rate of the device with the incident angle. A performance test system of the CTPV under practical weather conditions was built. The variation tendency of air temperature at inlet and outlet, instantaneous heat collection, output power, and photothermal and photoelectricity efficiency were analyzed.

The main conclusions are drawn as follows:

1. The light escape rate of the CPC and the CTPV was compared and calculated under the same conditions. When the incident angle was 12° , the light escape rate of the CTPV was 5.4%, which is 86.8% lower than that of CPC.
2. The maximum temperature difference between the inlet and the outlet of the heat exchange air of the CTPV was 23.7°C on sunny days. The maximum outlet temperature and the maximum instantaneous heat collection were 55.6°C and 306 W, respectively, and the total output power of solar cells was 474.4 W.
3. The experiment results showed that the highest total photothermal and photoelectricity efficiency of the CTPV could reach up to 60.4% and its average efficiency was 44.9%. As a result, the heat dissipation loss could be diminished by the greenhouse effect of the CTPV, and the output energy per unit heat collection area could be improved. This work can be regarded as a reference for the design and optimization of non-tracking CPC devices.

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Declarations

Conflict of interest The authors declare that there is no conflict of interests.

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