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Experimental and Comparison Study on Two Solar Dish Systems with a High Concentration Ratio

CHEN Haifei[1], LI Guiqiang[2,*], YANG Jie[1], ZHANG Fuwei [1], LIANG Ming[1], JI Jie[3,*]

1. School of Petroleum Engineering, Changzhou University, Changzhou 213164, China
2. School of Engineering, University of Hull, Hull HU6 7RX, UK
3. Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230026, China

Abstract: Two high concentrating solar systems have been established with dish concentrator and plane-mirrors array concentrator. In the paper, the thermal performance has been experimentally studied with jet water cooling device and flat microchannel water-cooled device. The experimental results show that the maximum surface temperature difference of the dish concentrating system is greater than 20°C, while the plane-mirrors array system is lower than 4°C. It indicates that the plane-mirrors array concentrator has better uniformity. As the concentration ratio increases, the electrical efficiency of the concentrating photovoltaic system gradually decreases. When the concentration ratio is 200, the electrical efficiency of the photovoltaic system is 25%. The concentration ratio of 500 times or less is considered to be a suitable value, and then the electrical efficiency can still exceed 20%. It is found that the plane-mirrors array solar system is more suitable for the photovoltaic system than dish type system, which is only suitable for thermal power generation system.

Keywords: high concentration ratio, thermal science, dish system, solar energy

1. Introduction

In order to solve the environmental problems caused by the overuse of non-renewable resources and the rapid development of the society, it is really urgent to develop clean and renewable energy such as solar energy. Photovoltaic (PV) technology, one of the important utilization patterns of solar energy, is widely concerned.

Low-concentration PV technology is a promising project because it can work with the fixed installation. A low concentrating photovoltaic/thermal system (CPV/T) on a quasi-parabolic concentrator consisting of plane-mirrors reflectors was designed, of which the concentrator characterizes the mirrors utilization ratio of 94.9% and overall optical efficiency of 55.5%. The system would achieve up to 59% overall efficiency [1]. Some novel solar systems for building south wall integration have been proposed [2–4]. In another study, a novel static concentrating PV system, which is appropriate to use in windows or glazing facades, has been designed [5].

Although low-concentration PV technology can be used with fixed installation, the high concentrating photovoltaic system has higher electrical efficiency,

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Corresponding authors: LI Guiqiang E-mails: guiqiang.li@hull.ac.uk
JI Jie jijie@ustc.edu.cn

which will show great potential in the future. A high concentrating photovoltaic/thermal (HCPV/T) module has been experimentally studied and compared with the HCPV module, which indicates that the HCPV/T module shows better performance with 26.5% electrical efficiency and additional 49.3% thermal efficiency [6]. A CPV system including the practical implementation and economic assessment was presented in the year 2017. The average cell efficiency for all basic modules in the dense array concentrator photovoltaic (DACPV) receiver was measured in the range from 35.0% to 36.1% and the system efficiency was measured only in the range between 16.1% and 17.4% [7]. The electrical conversion efficiency of a building façade integrated asymmetric compound parabolic photovoltaic (BFI-ACP-PV) coupled PCM system was increased by over 5% compared with a similar system without PCM integrated at the rear. This value increased by over 10% for an incident solar radiation intensity [8]. There are also many novel concentrators designed for increasing the overall efficiency and lowing the cost of construction [9–12]. In order to achieve a uniform light intensity distribution and an adjustable concentration ratio, many novel concentrators have been designed. A novel lens-walled compound parabolic concentrator (CPC) with air gap increases optical efficiency by more than 10% compared with the original lens-walled CPC. In addition, it is more uniform than that of the common mirror CPC [13]. Plane-mirrors array structure is applied to a solar photovoltaic/thermal (PV/T) system with triple-junction solar cells, which can provide PV/T module with a uniform light intensity distribution and an adjustable concentration ratio. The thermal conversion efficiency of the system can achieve about 48% to 52% and the theoretical photovoltaic conversion efficiency can reach 26% [14]. A novel asymmetric compound parabolic concentrator concentrating PV with uniform flux distribution has also been designed, which is beneficial for the PV output under concentrating illumination due to uniform flux distribution [15]. A recent simulation of a V-trough concentrator with photovoltaic module has also been proposed, and an advanced ray tracing software was used to determine the optimum design of the V-trough concentrator [16].

Many researchers use the secondary light homogenizing element to obtain a uniform light intensity distribution. However, such components not only increase system cost but also reduce the optical efficiency of the system. In this study, multi-disk structure and planar-mirrors array structure have been proposed to improve system uniformity. And two high concentrating solar systems with a high concentration ratio are presented. The performance of the system is compared with experimental data. The results show the plane-mirrors array concentrator has better uniformity.

2. Design of the Solar Systems

2.1 Description of a dish concentrator

A dish concentrator includes several small dishes instead of a large continuous parabolic dish. The purpose of this method is not only to reduce the difficulty and precision of making the large parabolic mirror but also to modularize the production of dish concentrators and make it more convenient to transport.

Some companies usually use resin to make the mould and paste the highly reflective film on its surface to form the corresponding parabolic mirror. This method is simple and easy to operate, but there are many problems in practical application such as corrosion. Another method is hot-bending annealing, which uses flat glass as a raw material. Flat glass must be softened at a high temperature and formed in a prior mould and anneals. This method requires a more professional hot-bending annealing process and a slight deviation will result in fragmentation of the glass mirror. The super-white low-iron glass on the surface of the parabolic objective lens is used to solve the above problem, which is formed by hot bending annealing. Then silver is plated on the lower surface and the multi-layer protective measures are added to the lower surface of the glass. Fig. 1 shows the whole dish concentrator that uses 9 parabolic mirrors, each of which is a square with a side length of 1.066 m. Nine parabolic dishes are installed in the corresponding position of the entire supporting frame.

Fig. 1 Experimental platform for dish concentrator

2.2 Introduction of plane-mirrors array concentrator

In order to obtain uniform light intensity distribution, a plane-mirrors array system is designed. The positions of plane-mirrors are usually calculated accurately, but this method requires high precision and the errors will be transmitted to each other, which is difficult in the actual installation process. So it is necessary to adopt a focus element to connect the plane-mirrors and the supporting frame, which is called the universal joint. It is not only the medium of connecting the supporting frame and the plane-mirrors but also can adjust the position of the plane-mirrors in three-dimensional space. Fig. 2 shows two different universal joint structures, but the basic principle is similar.

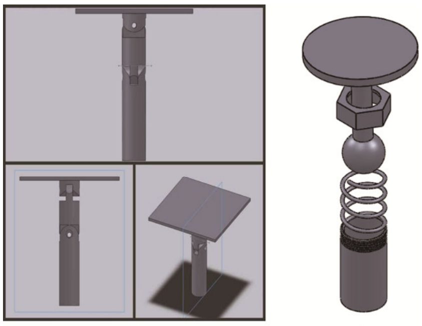


Fig. 2 (a) Bolted universal joint and (b) spherical universal joint

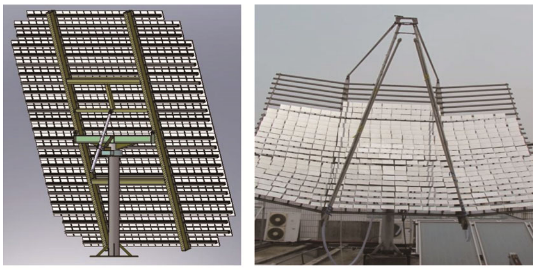


Fig. 3 (a) Schematic diagram and (b) physical drawing of plane mirror array concentrator

The system makes the solar light incident vertically to the main frame of the concentrator through a two-dimensional tracking device and adjusts the inclination position of each mirror by tracking the height and azimuth of the sun. The size of the focal spot receiver is the same as each plane-mirror, so it is convenient to change the concentrating ratio by increasing or reducing the number of plane-mirrors, thus achieving the purpose of adjustable focusing ratio. As can be seen in Fig. 3, 450 plane-mirrors are used in the plane-mirrors array concentrator.

2.3 Design of two-axis tracking system

A high concentrating photovoltaic system must include a high precision two-axis tracking device, which can track the elevation angle and azimuth angle of the sun at the same time. As is shown in Fig. 4, a rotary push-rod tracking system includes two motors. A stepping motor drives the rotary table to rotate the whole concentrator in a horizontal plane to track the azimuth angle of the sun and the other motor drives the push-rod to move the concentrator in the pitch direction to track the elevation angle of the sun.

2.4 Design of cooling system

When the concentrator accurately tracks the sunlight through a two-axis tracking device, the focal position of the concentrator will form a great energy flux density and raise the receiver's surface temperature. Because solar energy not only turns into electricity, but part of it also turns into heat. Meanwhile, the increase of surface temperature of photovoltaic cells will seriously affect the photoelectric conversion efficiency of the system. Therefore, it is necessary to take effective heat transfer measures to photovoltaic modules. Since the optical properties and heat flux density of the dish and plane mirrors systems are different, the cooling methods suitable for the corresponding systems are needed to get a better system performance, which have been studied in our previous publications [17–19]. Fig. 5 shows the jet water-cooled device of the dish concentrator and the flat microchannel water-cooled device of plane-mirrors array concentrator.

Fig. 4 Rotary push-rod tracking device

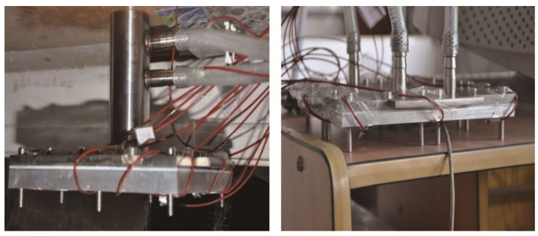


Fig. 5 (a) The jet water-cooled device and (b) the microchannel water cooling device

3. Experimental Method

Through the previous theoretical analysis, the focal spot of the dish concentrator can be expressed as

$$w = \frac{2r \tan 16'}{\cos \theta_r} \tag{1}$$

where r is the distance from the incident point to the focal surface of the concentrator; θ_r is the angle between the reflected beam and the optical axis.

$$r = \frac{2f}{1 + \cos \theta_r} \tag{2}$$

where f is the focal length.

$$n = \frac{a}{f} \tag{3}$$

where n is used to measure the brightness of concentrated images and a is the diameter of the concentrator.

Then the concentration ratio is

$$C=\left(\frac{nf}{w}\right)^2=\frac{n^2\left(1-\frac{n^2}{16}\right)^2}{4\tan^2 16'\left(1+\frac{n^2}{16}\right)^4} \tag{4}$$

$$h=\frac{a^2}{16f} \tag{5}$$

where h is the height of the dish concentrator that also is the distance from the outer edge to the ground.

Then the structure of the concentrator is shown in Table 1.

Table 1 The structure of the concentrator with different concentration ratio

C	500	1000
a	4.47 m	6.32 m
f	1.24 m	1.83 m
θ_r	83.99°	81.44°
h	1.01 m	1.36 m
w	0.2 m	0.2 m

In the experiment, a turbine flowmeter was used to measure the mass flow rate. T-type thermocouples were used to measure the ambient temperature, the temperature of PV cells and the inlet and outlet temperatures of the water. Before the PV module was set up, the temperature of the PV cell was measured with the temperature sensor that was inset at the back face of the cell. And a pyrheliometer (TBS-2-2) was used to measure the direct radiation. An infrared thermal imager was used to take thermal images to observe the distribution of heat flux in the focal plane. The output signals were all connected to a data logger (Agilent 34970A), which collected data every 10 s. The precision of each device is shown in Table 2.

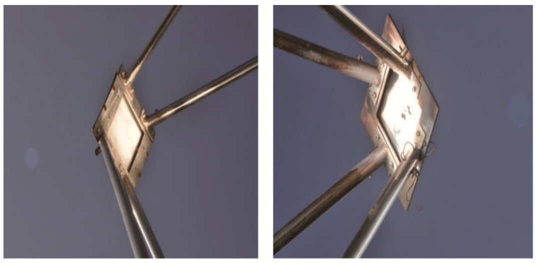
Table 2 The precision of each equipment

Device	Specification	Precision
Turbine flowmeter	LWGY-10	1%
Thermocouple	Copper-constantan, T-type	±0.5°C
Pyrheliometer	TBS-2-2	≤3%
Infrared thermal imager	Ti32	±0.04°C
Data logger	Agilent 34970A	/

After installing and debugging the two systems, the energy flux density distribution of the spot is shown in Fig. 6. The focal plane was photographed by using thermal infrared imager and the result is shown in Fig. 7. It can be clearly seen from the diagram that the energy flux density of the plane-mirrors array concentrator is more uniform while the dish concentrator still has local overheating phenomenon and the uniformity is poor.

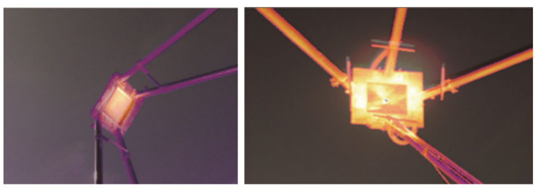
In order to improve the uniformity of the concentrating system, a self-made light funnel is added to the original system. As shown in Fig. 8, a light funnel is formed by folding aluminum mirror with high reflectivity. The left of Fig. 8 is the light funnel used for the plane-mirrors array concentrator. The right of Fig. 8 is the light funnel used for the dish concentrator. It can be seen from the diagram that during the long-term operation of the system, some “hot-spots” appear in the light funnel due to non-uniform light concentration of dish concentrator.

The temperature distribution of the concentrating surface is not uniform. It is difficult to obtain a complete temperature profile by measuring the temperature with thermocouples, as too many thermocouples can affect the heat transfer performance of the concentrator. So several typical locations can be chosen as representatives to study the temperature distribution of the concentrating surface. Four thermocouples are arranged as shown in Fig. 9. The radiators with thermocouples are installed in the focal points of the dish concentrator and the plane-mirrors array concentrator respectively. During the operation of the system, the excess heat is carried out by the water pump. Meanwhile, the surface temperatures of the radiator, inlet and outlet temperature and direct radiation are collected by data acquisition instrument.



(a) (b)

Fig. 6 The energy flux density of (a) plane-mirrors array concentrator and dish concentrator



(a) (b)

Fig. 7 Spot distribution of (a) plane-mirrors system under infrared thermal imager and (b) dish concentrating system under thermal imager

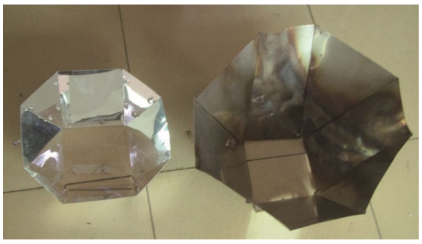


Fig. 8   Light funnels used in two high concentrating systems

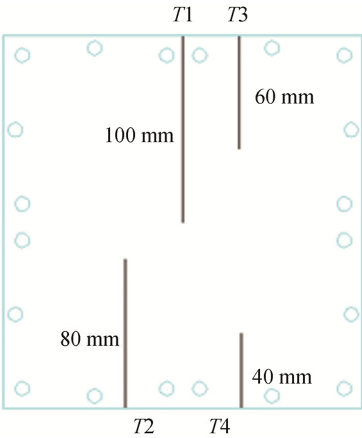


Fig. 9   Distribution of thermocouple on radiator's surface

4. Results and Discussions

The surface temperature distribution of the radiator in a dish concentrating system is shown in Figs. 10 and 11. The surface temperature distribution of the radiator in the plane-mirrors array concentrating system is shown in Figs. 12 and 13.

The above four images are measured under different irradiation conditions. It can be seen from Fig. 10 and Fig. 11 that the maximum surface temperature differences of radiator in dish concentrating system exceeds 20°C. As shown in Fig. 12 and Fig. 13 that the maximum surface temperature difference of radiator in planar-mirrors array system is about 2.5–4.1°C. Considering that the measuring accuracy of the thermocouple itself and the cooling water temperature rise along the direction of water flow, the results taken by the integrated thermal imager can be regarded as the uniform distribution of the energy flux density focused by the plane-mirrors array concentrator, which is suitable for high concentrating

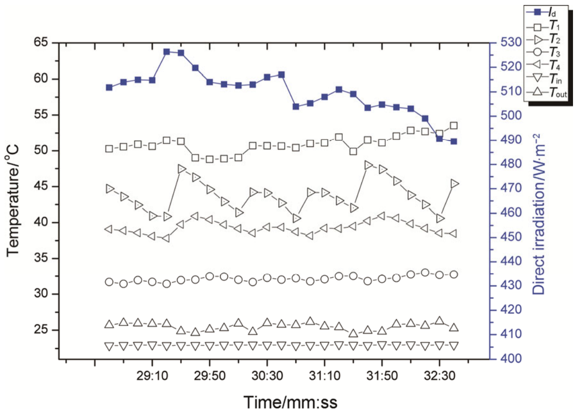


Fig. 10   Temperature distribution of the radiator of the dish concentrating system 1

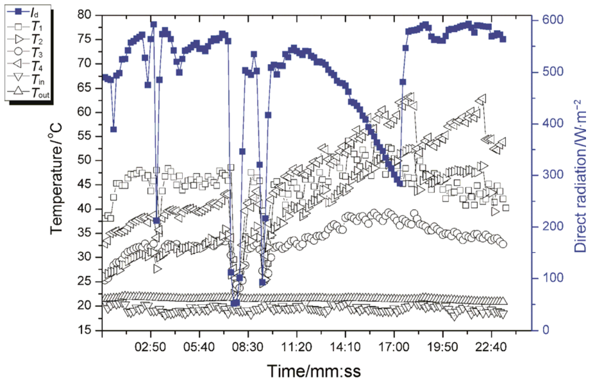


Fig. 11   Temperature distribution of the radiators of the dish concentrating system 2

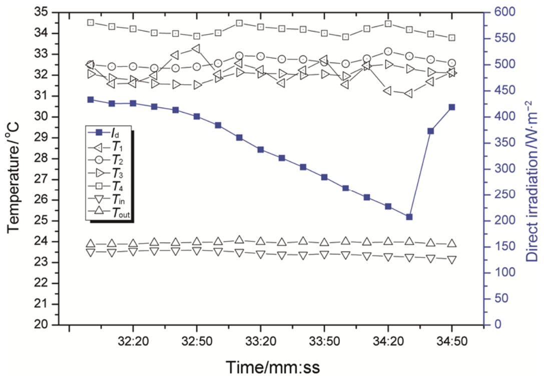


Fig. 12   Temperature distribution of radiators in plane-mirrors array concentrating system 1

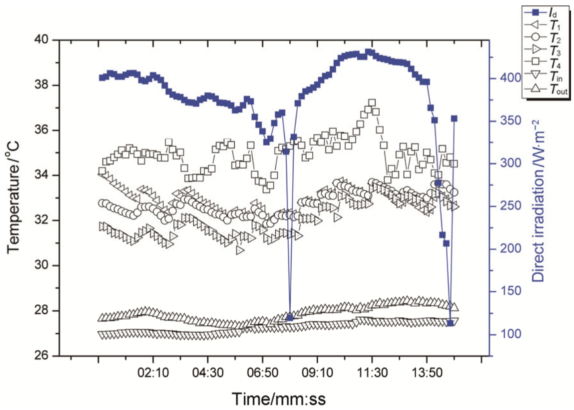


Fig. 13   Temperature distribution of radiators in plane-mirrors array concentrating system 2

photovoltaic system.

The concentrating photovoltaic system using the plane-mirrors concentrator can change the concentration ratio of the system by adjusting the number of plane-mirrors. Then, the thermal and electrical efficiency with photovoltaic cell T_c under different concentration ratios are shown in Fig. 14. When the concentration ratio is 200, the thermal efficiency of the system exceeds 45% and the electrical efficiency exceeds 25%. When the concentration ratio is 450, the thermal efficiency of the system exceeds 50%, but the electrical efficiency is about 20%. When the concentration ratio continues to increase, even when it exceeds 500, the temperature of the cell will exceed 100°C, and the photoelectric conversion efficiency of the cell will be greatly reduced. Therefore, the plane-mirrors array system is applicable in the case where the concentration ratio is less than 500. In addition, considering the working temperature of the PV cell, the selection of water flow rate should match the concentration ratio to get a better electrical performance.

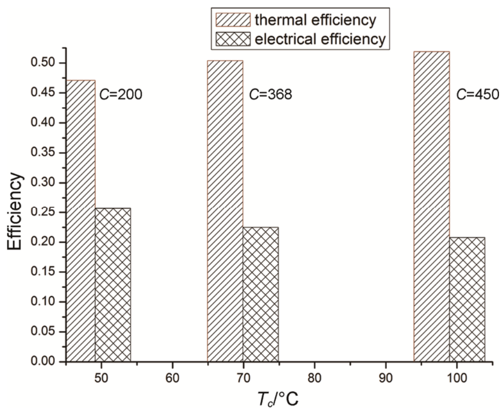


Fig. 14 The thermal and electrical efficiency with T_c under different concentration ratios

5. Conclusions

In this paper, the dish concentrator and the plane-mirrors array concentrator are developed and the experimental platform is built. Cooling devices are developed for two different focusing modes: the dish concentrating system uses a jet water-cooled device while the plane-mirrors array system uses a flat water-cooled device.

Two different concentrators are studied experimentally. The results show that the maximum surface temperature difference of radiator in dish concentrating system exceeds 20°C and that in plane-mirrors array system is about 2.5–4.1°C. Therefore, the plane-mirrors array concentrator has better uniformity and is suitable for high concentrating photovoltaic systems. The dish concentrator is not suitable for HCPV system because of its uneven concentration ratio, but this kind of system can still be applied in solar thermal power generation system.

Acknowledgements

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