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Design and study of an irradiance distribution measuring method based on a photodiode array

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ABSTRACT

In this work, an irradiance distribution measuring method based on a photodiode array was proposed to measure the irradiance distribution of truncated compound parabolic concentrators (CPCs). Firstly, truncated CPCs were designed and 3-D printed. Then twelve photodiodes were soldered on a printed circuit board to measure the irradiance distribution of CPCs. Besides, a box was manufactured to support the board and CPCs. Irradiance distribution of CPCs was measured under the illumination of Oriel AAA class solar simulator. Corresponding non-uniform factors of irradiance profiles of CPCs were evaluated based on the concept of standard deviation. Experimental results were compared with simulated irradiance profiles of CPCs. A maximum relative error of 13.1% was found between experimental and theoretical results, which verified the feasibility of the proposed photodiode array based irradiance distribution measuring method.

Keywords: irradiance distribution measurement, photodiode array, truncated compound parabolic concentrator, non-uniform irradiance

NONMENCLATURE

Abbreviations	
CPC	Compound Parabolic Concentrator
PCB	Printed Circuit Board
Symbols	
G	Irradiance (W/m^2)
I	Current (A)
i	Label of photodiodes
n	Number of photodiodes

1. INTRODUCTION

As a promising renewable energy, solar energy has drawn increasing attention owing to its abundance, universal availability and non-pollution. Photovoltaic (PV) is one of the most common utilization of solar energy which can convert the energy of photon into electricity directly. Since the electrical efficiency of PV panel decreases with increasing temperature, cooling is attached at the back of PV for another purpose of heat recovery. Thus the photovoltaic/thermal (PV/T) system comes into being. To increase the solar flux on the plane of PV/T module, a concentrator is adopted. However, non-uniform irradiance distribution is also introduced by the concentrator. Non-uniform irradiance distribution causes not only additional heat loss [1], but also extra ohm loss [2]. Hence both electrical and thermal output experience a decrease. To avoid the decreasing efficiency with increasing non-uniformity of irradiance, it's important and necessary to find out the irradiance distribution of the concentrator.

To figure out the irradiance distribution of the concentrator, both theoretical and experimental methods can be used. Theoretically, ray tracing simulation is conducted based on Monte Carlo Ray Tracing method either by programming [3] [4] [5] or using software such as LightTools [6], Zemax [7], Tonatiuh [8] and TracePro [9]. However, ray tracing simulation is somewhat ideal and does not coincide with practical setup where manufacture and installation errors are inevitable. Thus measurement of the irradiance distribution is quite essential. Experimentally, both direct and indirect measuring were studied. For indirect measuring, a charge-coupled device camera combined with a Lambertian target is applied in common. For direct measuring, photodiode [10], calorimeter [11] and thermo-gage [1] were used based on their current or temperature response to solar irradiance. Riffelmann et al. [12] applied both direct and indirect methods to measure the irradiance distribution in the focal region of a parabolic trough collector. The direct method was based on a photodiode array. But the whole assembly was not installed on the surface of absorber exactly. The indirect method was camera-target-method in which the complicated image processing and amendment were employed to rebuild the irradiance distribution.

In principle, it remains difficulties and challenges to measure the irradiance distribution accurately and easily. For indirect measuring, the precision lies on complex image processing and amendment. For direct measuring, the precision depends a lot on the dimension of the sensor whatever principle it's based on. In the present study, we aim at measuring the irradiance distribution of truncated CPCs based on a photodiode array. Firstly, truncated CPCs were designed and manufactured by 3-D printing. Then twelve photodiodes with chip size of 1mm×1mm were soldered on a printed circuit board (PCB) to form an array of 1×12. Besides, a box was manufactured to support the PCB and CPCs. Finally, irradiance distribution of CPCs was measured under the illumination of Oriel AAA class solar simulator and compared with simulated results by TracePro.

2. MATERIAL AND METHODS

Fig. 1 shows the whole experimental setup including Oriel AAA class solar simulator (non-uniformity is less than 2%, aperture size 15mm×15mm), the assembly of CPC and photodiode array, data acquisition system and a PC. Fig. 2 displays the assembly of CPC and photodiode array. When the light is on, photodiodes generate currents proportional to their local irradiance. Then current signals are transmitted to the data acquisition system and processed by the PC. To obtain the irradiance distribution of CPCs, the currents of photodiodes are measured with and without CPCs. If we assume the currents of photodiodes without CPCs are $I_{1,ref}$, $I_{2,ref}$,⋯, $I_{n,ref}$, and the currents of photodiodes with CPC are I_1, I_2,⋯, I_n, then the local irradiances can be calculated by:

$$G_i = \frac{I_i}{I_{i,ref}} G_{ref},\ i = 1, 2, \cdots, n \quad (1)$$

where G_{ref} is 1000W/m^2. The irradiance distribution of CPCs can be obtained by combination of local irradiances at the positions of photodiodes.

2.1 Design and manufacture of CPCs

Two truncated CPCs are designed based on the method of eliminating multiple reflection, which was elaborated and defined as HEMR and LEMR in our previous work [13]. To make the whole assembly inside the aperture of solar simulator, the width of outlet aperture and geometric concentration ratio of CPC are defined as 3 mm and 4 respectively. To manufacture the concentrators, the bulk of a pair of CPCs is 3-D printed at first. Then surface of parabolas of CPCs is covered by reflective film with average reflectivity of 0.94. Fig. 3 displays the pictures of HEMR and LEMR concentrators.

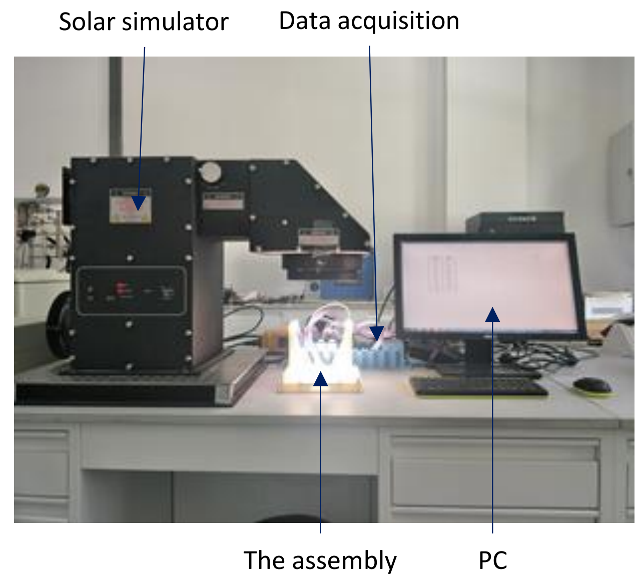

Fig. 1 Picture of experimental setup.

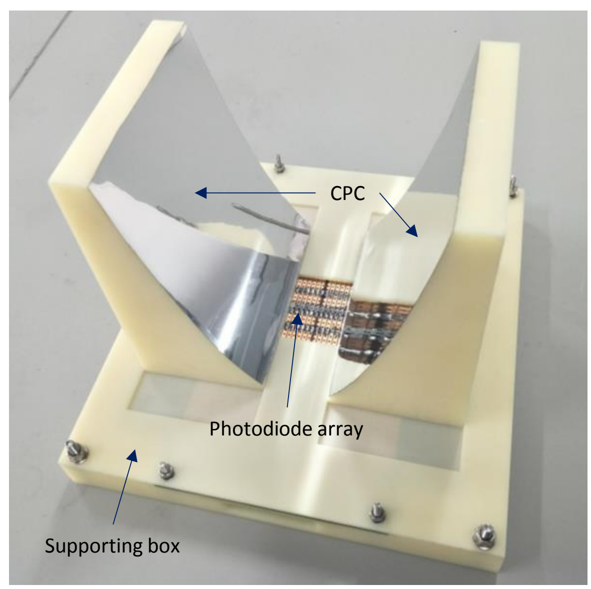

Fig. 2 Picture of the assembly.

2.2 Photodiode array

To make the measurement as accurate as possible, photodiode (OSRAM SFH 2400) with chip size of

1mm×1mm is chosen as the element of the measuring array. A printed circuit board (PCB) is used to support the photodiodes by soldering. Restricted by the dimension of encapsulating materials and strips on PCB, the distance between adjacent photodiodes is 2.5mm. Thus 12 photodiodes are exactly enough to cover the concentration plane of CPC. The PCB with 12 photodiodes soldered on the surface is shown in Fig. 4.

Fig. 3 Pictures of 3-D printed HEMR (up) and LEMR (down)

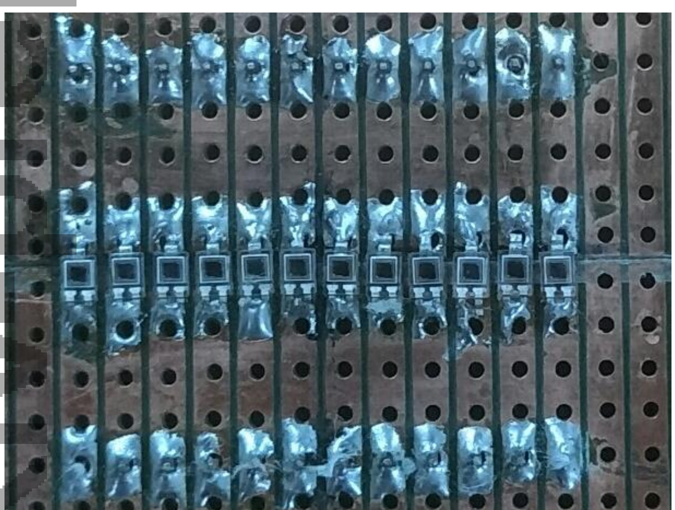
Fig. 4 Irradiance distribution of HEMR concentrator

3. THEORY

To validate the experimental results, irradiance distribution of CPCs is simulated by TracePro. Fig. 5 shows schematic of rays tracing simulation of CPCs in TracePro. Parabolas of the concentrator are defined as reflectors with reflectivity of 0.94. Upper surface of the receiver is defined as a perfect absorber with 100% absorptivity. Then a rectangular source (direct normal irradiance, DNI) is defined over the inlet aperture of the concentrator. For DNI source, grid pattern is random and 2.5 million rays are emitted and uniformly distributed. Irradiance is set to be 1000W/m^2 and direction of rays is parallel to the axis of the concentrator (y axis).

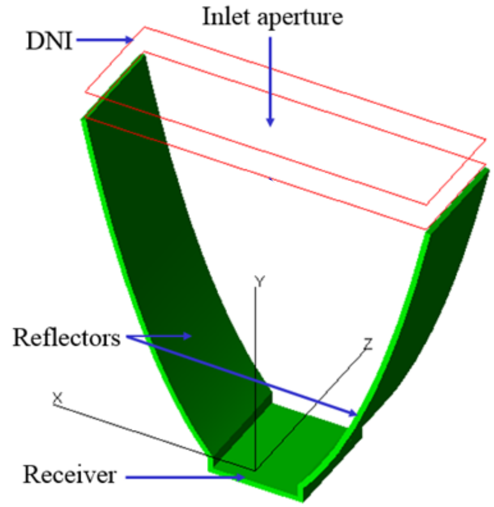

Fig. 5 Schematic of rays tracing simulation in TracePro

4. RESULTS AND DISCUSSION

Figs. 6 and 7 show the irradiance distribution of HEMR and LEMR concentrators by simulation and measurement respectively. From Fig. 6, in HEMR case, irradiance distribution in a wide range of concentration plane is quite uniform. But the irradiance near the edge decreases a lot. From Fig. 7, in LEMR case, irradiance distribution seems more non-uniform as two symmetric peaks and a valley in the center of concentration plane can be seen from the profile. However, quantified non-uniform factor based on standard deviation [14] reveals that non-uniformities in the cases of HEMR and LEMR are 0.711 and 0.733 by experiment, which are a little higher than those by simulation (0.636 and 0.569).

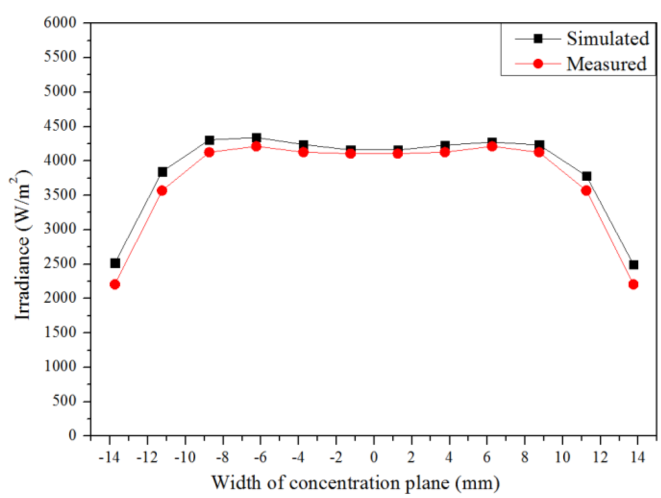

Fig. 6 Irradiance distribution of HEMR concentrator

From Figs. 6 and 7, it can be further figured out that measured irradiance distribution by photodiode array coincides with the simulated one in both cases of HEMR and LEMR. The largest relative error in the case of HEMR exists at the margin of the width of concentration plane with a relative error of 12.42%. While the largest relative error in the case of LEMR exists at the center of concentration plane with a relative error of 13.14%. Moreover, a relative error of 12.65% for photodiode in the edge of the LEMR case can't be neglected.

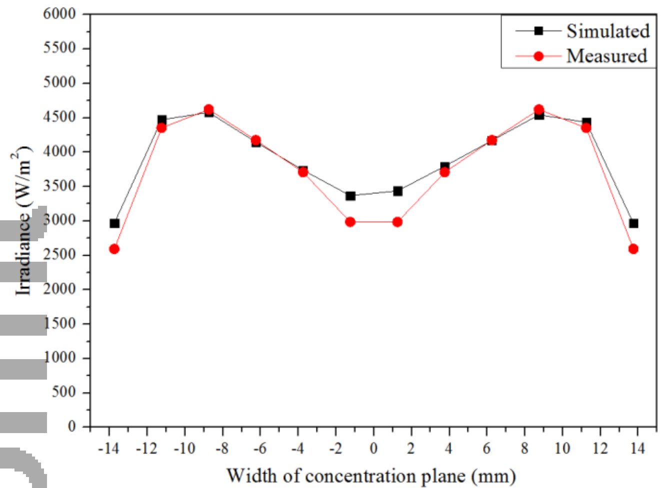

Fig. 7 Irradiance distribution of LEMR concentrator

The reason for large error in the edge or center of concentration plane can be explained by the principle of edge concentrating. According to edge concentrating principle, the range of concentration is decided by incident rays at the edges of concentrator. As shown in Fig. 8, for HEMR concentrator, the reflection from one parabola (C_hB_h) covers a wide range (A_hF_{h1}) of the concentration plane. Reflected lines (C_hA_h and B_hF_{h1}) of incident rays (M_hC_h and N_hB_h) at the edges (top and bottom) reach the edges of concentration plane. Thus the measurement error at the edge will increase due to various errors such as shadow and manufacture error of parabolas. As shown in Fig. 9, for LEMR concentrator, the reflection from one parabola (C_lB_l) covers just half (A_lF_{l1}) of concentration plane. The reflected line (C_lA_l) of incident ray (M_lC_l) at the top reaches the midpoint (A_l) of the concentrator plane. While the reflected line (B_lF_{l1}) of incident ray (N_lB_l) at the bottom reaches the edge of the concentrator plane. Therefore the measurement error at the edge and the center will increase in the case of LEMR.

5. CONCLUSION

In the present study, an irradiance distribution measuring method based on a photodiode array was developed and applied to measure the irradiance distribution of two truncated CPCs, HEMR and LEMR concentrators. Above all, HEMR and LEMR concentrators were designed and 3-D printed. Subsequently, twelve photodiodes were soldered on a printed circuit board to compose an array. Irradiance distribution of HEMR and LEMR concentrators was measured under the illumination of Oriel AAA class solar simulator. Corresponding non-uniform factors of irradiance profiles of CPCs were evaluated based on the concept of standard deviation. Experimental results were compared with simulated irradiance profiles of HEMR and LEMR concentrators. A maximum relative error of 13.1% existed in the center of concentration plane in the case of LEMR concentrator, which verified the feasibility of the presented photodiode array based irradiance distribution measuring method. Future work may have to be conducted on further improving the precision of measurement based on the photodiode array.

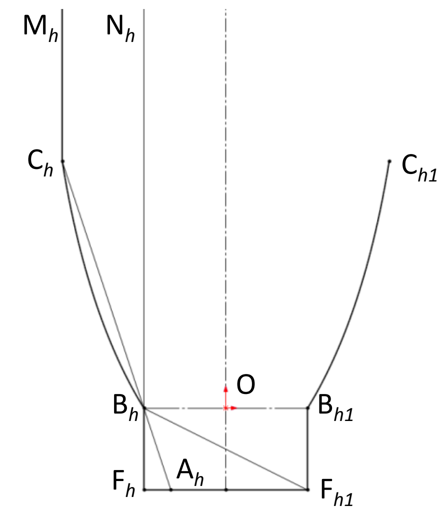

Fig. 8 Principle of HEMR concentrator

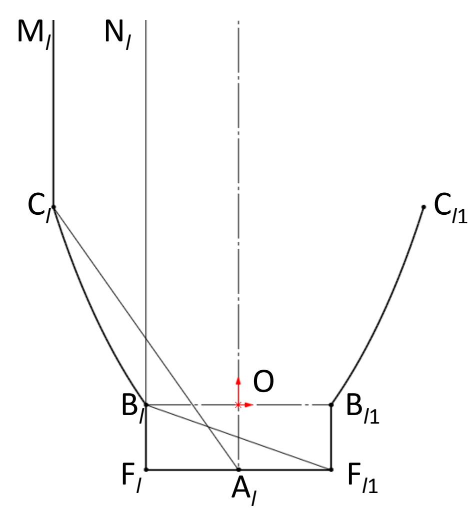

Fig. 9 Principle of LEMR concentrator

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