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Research Paper

Design and experimental investigation of a Multi-segment plate concentrated photovoltaic solar energy system

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HIGHLIGHTS

- A multi-segment plate concentrated photovoltaic solar energy system was proposed.
- A prototype of this new concentrator was developed for experimental investigation.
- Experimental investigation results showed a good concentrating uniformity.

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ABSTRACT

Solar energy is one of the most promising renewable energies and meaningful for the sustainable development of energy source. A multi-segment plate concentrated photovoltaic (CPV) solar power system was proposed in this paper, the design principle of the multi-segment plate concentrator of this solar power system was given, which could provide uniform solar radiation flux density distribution on solar cells. A prototype of this multi-segment plate CPV solar power system was developed for the experimental study, aiming at the investigations of solar radiation flux density distribution and PV performances under this concentrator design. The experimental results showed that the solar radiation flux density distribution provided by the multi-segment plate concentrator had a good uniformity, and the number and temperature of solar cells both influence the photoelectric transformation efficiency of the CPV solar power system.

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1. Introduction

How to increase the photoelectric transformation efficiency of solar cells and reduce the cost is always the key problem for solar PV power generation. One of the suggested effective approaches to reduce the amount of solar cells is concentrating the incident sun light using inexpensive optical components [1–5]. Traditional concentrators, such as parabolic dish and parabolic trough concentrators [6], normally employ curved reflective surfaces, which make the concentrated solar radiation flux density distribution on the focal plane (or solar cells) non-uniform and result in low solar energy conversion efficiency [7,8]. The output current from a solar cell depends on the incident flux and solar cells are normally connected together in series and parallel.

Solar radiation is nearly parallel light with a tiny solid angle of about 32′ [9], thereby its flux density distribution is nearly uniform. Plane mirror can reflect solar light with almost the same uniformity. If a concentrator is comprised of good designed plane mirrors in instead of curved reflecting surface, it could make the concentrating light density distribution on solar cells more uniform. Chong et al. proposed a non-imaging planar concentrator attached to on-axis sun-tracker to produce a uniformly illuminated spot through the superposition of all the flat mirror images at the target [10]. Jiang et al. developed two kinds of multi-plane mirror reflective concentrators for solar PV power generation and carried out the preliminary experimental investigations [11]. In this study, a multi-segment plate concentrator for solar PV power generation was proposed, which could provide uniform solar radiation flux density distribution on solar cells. And a prototype of this multi-segment plate CPV system was developed to investigate the solar radiation flux density distribution and PV performances.

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2. Design of the multi-segment plate concentrator

The schematic diagram of the multi-segment plate concentrator is presented in Fig. 1. The concentrator was comprised of many mirror planes. The incident solar radiation was vertical to the X-axis. PQ was the focal plane with slope angle α. P_i and P_{i+1} were the start point and the end point for Plane i, respectively. β_i and K_i were the slope angle and there was $K_i = \tan\beta_i$. N_i was the normal line of Plane i. The incident angle and reflected angle of Plane i were γ_{i1} and γ_{i2}. According to the geometric relationship, there should be $\gamma_{i1} = \gamma_{i2} = \beta_i$. To maximally utilize the area of the concentrator, the start point P_1 of the first plane mirror and Point Q had the same X-axis value, and all plane mirrors were connected end to end. In the coordinate system, there were $X_P = 0$, $X_Q = W\cos\alpha$ and $Z_Q = Z_P + W\sin\alpha$, where W was the width of the focal plane (or the width of solar cells). The position of Point Q in Z-axis could also be expressed as following:

$$Z_Q = K_{PQ}(X_{P_1} - X_P) + Z_P \tag{1}$$

where K_{PQ} was equal to $\tan\alpha$. The coordinate values of Point P_1 of the first plane mirror were $X_{P1} = W\cos\alpha$ and $Z_{P1} = 0$. For the first plane mirror, there was $\theta_1 = \pi/2 - \gamma_{11} - \gamma_{12} = \pi/2 - 2\beta_1$. Thus, its slope could be calculated as:

$$K_1 = \tan\beta_1 = \frac{Z_{P_1} - Z_P}{X_{P_1}} + \sqrt{\left(\frac{Z_{P_1} - Z_P}{X_{P_1}}\right)^2 + 1} \tag{2}$$

The equation of line P_1P_2 was:

$$Z = K_1(X - X_{P_1}) + Z_{P_1} \tag{3}$$

The reflection lines PP_1 and QP_2 were parallel, therefore the equation of line QP_2 could be expressed as:

$$\begin{aligned} Z &= K_{PP_1}(X - X_Q) + Z_Q \\ &= -\tan\theta_1(X - W\cos\alpha) + Z_P + W\sin\alpha \end{aligned} \tag{4}$$

According to Eqs. (3) and (4), the coordinate values of the end point P_2 of the first plane could be expressed as following:

$$X_{P_2} = \frac{(PP_1 + W\sin\alpha)X_{P_1} - (Z_{P_1} - Z_P)W\cos\alpha}{PP_1} \tag{5}$$

$$Z_{P_2} = \frac{(Z_{P_1} - Z_P)(PP_1 + Z_{P_1} - Z_P)\left(1 - \frac{W\cos\alpha}{X_{P_1}}\right)}{PP_1} - \frac{(Z_{P_1} - Z_P)Z_{P_1}}{PP_1} + \frac{(PP_1 + Z_{P_1} - Z_P)(Z_P + W\sin\alpha)}{PP_1} \tag{6}$$

where PP_1 was the length between P and P_1 and there was $PP_1 = \sqrt{(Z_P - Z_{P_1})^2 + X_{P_1}^2}$.

Similarly we could obtain K_i and the coordinate positions of the end point P_{i+1} of Plane i as follows:

$$K_i = \frac{Z_{P_i} - Z_P}{X_{P_i}} + \sqrt{\left(\frac{Z_{P_i} - Z_P}{X_{P_i}}\right)^2 + 1} \tag{7}$$

$$X_{P_{i+1}} = \frac{(PP_i + W\sin\alpha)X_{P_i} - (Z_{P_i} - Z_P)W\cos\alpha}{PP_i} \tag{8}$$

$$Z_{P_{i+1}} = \frac{(Z_{P_i} - Z_P)(PP_i + Z_{P_i} - Z_P)\left(1 - \frac{W\cos\alpha}{X_{P_i}}\right)}{PP_i} - \frac{(Z_{P_i} - Z_P)Z_{P_i}}{PP_i} + \frac{(PP_i + Z_{P_i} - Z_P)(Z_P + W\sin\alpha)}{PP_i} \tag{9}$$

where PP_i was the length between P and P_i and there was $PP_i = \sqrt{(Z_P - Z_{P_i})^2 + X_{P_i}^2}$.

According to the slope and coordinate values of the start and end points of every plane mirror, the width of Plane i was:

$$W_i = \sqrt{1 + K_i^2}\,|X_{P_{i+1}} - X_{P_i}| \tag{10}$$

Based on Eqs. (1)–(10), the structure of the whole multi-segment plate concentrator could be obtained. The geometric concentrating ratio CR was equal to the ratio of W and the width of concentrator:

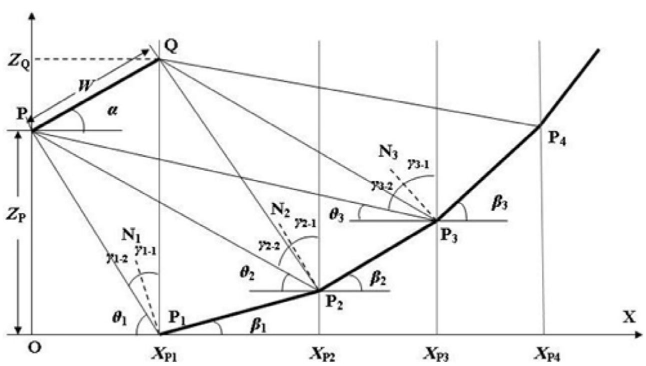

Fig. 1. Schematic diagram of the multi-segment plate concentrator.

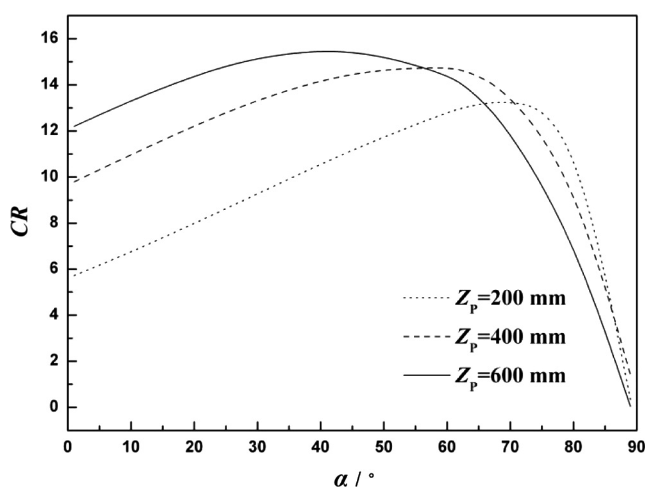

Fig. 2. The relationship between CR and α (W = 62.5 mm).

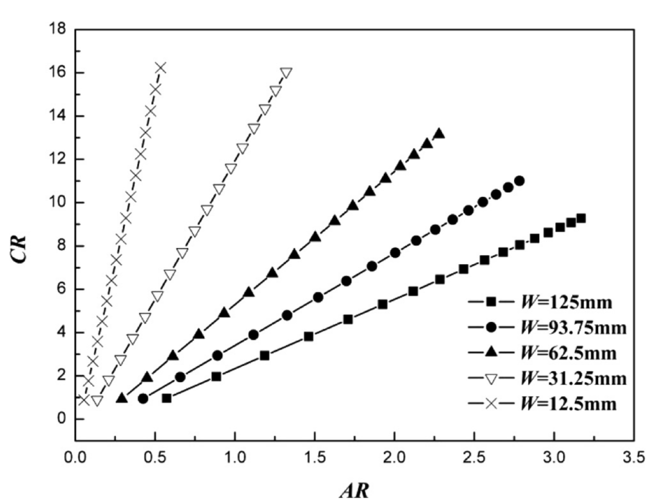

Fig. 3. The relationship between CR and AR.

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