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Optimization design and performance analysis of a novel asymmetric compound parabolic concentrator with rotation angle for building application

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ABSTRACT

A novel asymmetric lens-walled compound parabolic concentrator (ALCPC) for integration with the building south wall was proposed and manufactured. Besides of the asymmetric lens-walled structure, the special rotation angle at the bottom is also introduced to optimize the performance. The electrical and optical performance of the ALCPC-PV was detailed analyzed through the experiment and ray tracing simulation. The indoor experiment was conducted by a solar simulator (Oriel Sol3A Model 90943A) from Newport Corporation at the dark environment with the temperature of 25 °C. Form the experiment results, the ALCPC increases the maximum power by a ratio of 1.74x compared to the bare cell. The decrease of the geometric concentration ratio is mainly due to manufacturing errors, mismatch losses, series resistance losses, etc. The optical performance of the ALCPC was also investigated by the software Lighttools, and the optical efficiency and the distribution percentage of the energy collected through the total internal reflection and the specular reflection at different incidence angles are identified at various incidence angles. A good agreement is observed between the experiment results and the ray tracing results. The optical efficiency at the incidence angles of 0–60° is all within 90% of its peak value which means that the proposed ALCPC can achieve 60° acceptance angle with high optical efficiency that it shows a good potential as a static concentrator for the building south wall integration.

1. Introduction

With the rapid development of the industry and agriculture, more and more fossil fuel has been consumed and the extension use of it has resulted in a series of serious environment pollution problems (Jaaz et al., 2017; Nicoletti et al., 2015; Omer, 2008). The world energy consumption will reach 750 million kilowatts in 2020 which would be 50–80% higher than 1990 levels and buildings contribute around 40% to the total world annual energy consumption (Omer, 2008). In order to achieve the solutions to the environment pollution problems at present, the long–term focus on sustainable development is necessary. In this respect, renewable energy resource such as photovoltaic (PV) to meet the needs in the buildings seems to be one of the most efficient methods to alleviate the pressure on the traditional energy. PV as one of the renewable energy technologies, which converts the solar energy directly into the electricity, has been achieving a sharp growth during the last decades (Tiwari et al., 2011; G. Li et al., 2016; X. Li et al., 2016). As for the BICPV or BICPV/T systems, the static concentrators are an interesting topic because they are more suitable for building integration, which will also reduce the material in a PV module to achieve a cheaper PV system (Muhammad-Sukki et al., 2011; Swanson, 2000) and harvest a higher temperature energy source. The concentrator is a device usually makes use of geometrical optics in the design of reflective and/or refractive types of concentrating devices to focus the solar flux onto a receiver module where the PV cell is attached (Muhammad-Sukki et al., 2010; Chong et al., 2013).

There are many researchers have done a series work on the different concentrator designs since 1960s, among which the compound parabolic concentrator (CPC) is a very interesting topic, which was invented in U.S in 1970s (Winston, 1974; Rabl et al., 1980) and it has been widely studied all over the word. Goodman et al., 1976 used the dielectric material to make a solid-dielectric compound parabolic concentrators which collected sun rays by the way of the total internal reflection that produced a 5.7 times larger short circuit current than that of bare solar cells and using dielectric material to form the dielectric CPC is an effective way to increase the half acceptance angle and optical efficiency by means of the refraction and the total internal reflection (Hull, 1989). Cooper et al., 2013 designed a kind of CPC with

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Nomenclature

C	geometric concentration ratio
I	current, mA
Isc	short circuit current, mA
I_{sc}^{with}	the short circuit current of the concentrating PV, mA
$I_{sc}^{without}$	the short circuit of the non-concentrating PV, mA
$Q_{absorber}$	the total energy collected by the absorber, W
Q_d	the energy reaches the absorber directly, W
Q_{sf}	the energy collected through the specular reflection, W
P_{max}	maximum power, W
Q_{tsf}	the energy collected through the total internal reflection, W
$Q_{sf,\ t}$	the total energy which experienced the specular reflection including the absorption of the mirror, W

Greek symbols

α	the value of the specular reflectivity
θ	incidence angle
β	rotation angle of the optimization structure of the ALCPC
η_{opt}	optical efficiency of the concentrator
$\eta_{opt,ac}$	actual optical efficiency of the concentrator
θNS	the N–S projected solar altitude angle

polygonal apertures, and investigated the optical performance of it by Monte Carlo ray-tracing which revealed that Polygonal CPCs show promise as less expensive alternatives to the CPC for actual applications. Abu-Bakar et al. (2016) described a rotationally asymmetrical compound parabolic concentrator (RACPC), and the experiment research on the RACPC validated that the RACPC increases the short circuit current by 3.01x and the maximum power by 3.33x when compared with a bare solar cell. Su et al. (2012) together with Li et al. (2013) proposed the lens-walled structure for the CPC whose advantages can be concluded as more uniform flux distribution and larger acceptance angle than those of the mirror CPC and 80% optical performance of the dielectric CPC but less dielectric material with the same geometrical concentration ratio. Then Li et al. (2014a,b, 2015a,b), G. Li et al. (2016) and X. Li et al. (2016) further proposed a novel symmetric lens-walled CPC which adopted both the total internal reflection and the specular reflection to collect sun rays. This structure can improve the optical efficiency by more than 10% and is more uniform compared to the original lens-walled CPC (Li et al., 2015a,b) and they built a photovoltaic/thermal (PV/T) system based on the lens-walled CPC with air gap which can both save the PV materials and obtain a lower heat loss (Li et al., 2015a,b). Besides the CPC, there are also other kinds of concentrators that has been proposed and investigated. Canavarro et al., 2016 proposed a Compound Elliptical-type Concentrator (CEC) aimed at pushing to the limits the concentration achieved.

As for the application on the buildings, concentrating Photovoltaic (CPV) systems have plenty of advantages as compared to the conventional flat panel devices, such as: PV cell shows a higher electrical conversion efficiency, efficient use of the space, the PV cell that is needed for the building decreases which will reduce the use of toxic products involved in the process of the PV cell's production and the PV system will be cheaper (Li et al., 2015a,b). However the features of the solar concentrator for the application on buildings are obvious, such as combining with the building façade or roof as a static concentrator without a tracking system or seasonally adjustment, having a larger acceptance angle and higher optical efficiency, having a more uniform flux distribution to ensure the high PV or thermal characteristics (Li et al., 2014a,b). There are also many researchers have made their efforts in designing and integrating solar concentrators with buildings. Renno and Petito, 2013 designed a concentrating PV thermal system that was able to provide the electricity for the domestic use and recover the solar cell thermal energy to both supply heat for domestic application and enhance the performance of the solar cell. Muhammad-Sukki et al., 2014 presented a novel mirror symmetrical dielectric total internal reflection concentrator to increase the electricity production and reduce the PV cell material for BI (Building integration) application. Mallick et al. (2004, 2006, 2007) designed a novel asymmetric CPC which consists of two different parabolas, and the simulation and experiment results showed that it is feasible to be integrated with building façade at Northern Ireland (54°36′N, 5°37′W) and the experiments revealed that the asymmetric mirror CPC (with geometric concentration ratio of 2.0X) increased the PV power by 62% and a maximum power ratio of 2.01 was observed for a dielectric asymmetric CPC (with geometric concentration ratio of 2.45X). Furthermore, Sharma et al. (2016) further adopted the PCM (Phase Change Material) material to enhance the performance of the asymmetric CPC for BI application, which can increase the electrical efficiency by 7.7%. Mammo et al. (2012) analyzed the reflective 3D crossed compound parabolic-based photovoltaic module (3D CCPC PV) for building integrated photovoltaic applications, which achieved a 3.0x increase in the maximum power concentration compared to the similar type of non-concentrating module although an optical efficiency deviation of 19.4% between the 3D ray tracing simulation and experiment results was found.

It can been seen clearly from the above presentation that the advantages of the BICPV systems are obvious, and many researchers have devoted their efforts at the concentrator design and the application of it on the buildings, especially in the area of the CPC and its optimization structure for it is economical friendly. However, recent researches paid more attention on the symmetric static concentrators for the application on the building roofs, while the symmetric concentrators for integration with the building south wall are mainly focused on the mirror or dielectric compound parabolic concentrator. In previous studies, the advantages of lens-walled structure for the symmetric CPC for integration with the building roof has been proved, such as larger acceptance angle; more uniform flux distribution; less dielectric material (Li et al., 2013, 2014). However for the integration with the building south wall, the structure of the lens-walled CPC has not been well designed. Considering the characteristics of the integration with the building south wall, the asymmetric concentrator might be a better choice. So that, a novel asymmetric lens-walled CPC (ALCPC) for integration with the building south wall is proposed in this paper. And at different latitude areas, the incidence angles of the sun rays may vary a lot. In order to make the ALCPC more suitable for different areas, besides of the asymmetric lens-walled structure, the special rotation angle at the bottom is also introduced to optimize the performance.

2. The description of the ALCPC and its optimization structure

The structure of the asymmetric lens-walled structure is illustrated in Fig. 1(a). The profile of it can be described as following: the outer contour of the lens is composed of two asymmetric compound parabola curves MP and NQ, and half acceptance angles of them are 42°and 0°, respectively. The curves MP' and NQ' are rotated around their top end points P and Q toward the inside by a certain degree respectively to form the lens structure. Then the lens structure is truncated at P' and Q'. The distance between MN and $M'N'$ is the base height. The geometrical concentration ratio of the ALCPC is 2.4X, according to Eq. (1). Detailed parameters are listed in Table 1.

$$C = \frac{P'Q'}{MN} \tag{1}$$

The angle between the normal of the base of the ALCPC and the incident ray θ is defined as the incidence angle.