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Optical design and experiment evaluation of a novel asymmetric compound parabolic concentrator (ACPC) integration with PV for building south wall application

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Abstract. Compound parabolic concentrator (CPC) as a typical low-concentration-ratio concentrator is an interesting topic for it can work as the static concentrator without any additional tracking systems or seasonal adjustments, which shows a promising concept of introducing the concentrating PV technology for building application. Therefore, based on the compound parabolic curves, a novel asymmetric compound parabolic concentrator (ACPC) is proposed in this paper for building south wall integration. The optical model of the ACPC is built by the software Lighttools to study its optical performance, and the structure parameters of it are optimized through the optical simulation. Then the prototype of the ACPC integrated with the PV cell as the ACPC-PV module is manufactured and assembled. The indoor experiments by the solar simulator (Oriel Sol3A Model 90943A) from the Newport Corporation at the dark environment with the temperature of 25 °C are conducted to study the electrical performance of the ACPC-PV module. The simulation and experiment results show that the acceptance range of the ACPC with the geometric concentration ratio of 2.4X can be 65° with high optical efficiency. A good agreement is observed between the simulation and experiment results despite the deviation of around 13% which is inevitable due to all kinds of errors, such as manufacturing errors, mismatch losses, series resistance losses, etc.

Keywords: Asymmetric; Compound parabolic concentrator; Concentrating photovoltaic; Optical performance; Electrical performance

1. Introduction

With the rapid development of the society and the vast consumption of the fossil fuels, the environmental problems are becoming more and more serious. It has been stated that the world energy consumption will soar into 750 million kilowatts in 2020 which would be 50–80% higher than 1990 levels and the energy consumption in buildings has been steadily increasing and contributing up to more than 40% of the total energy use in developed countries. For developing countries, the share of building energy consumption is less, but, as the growth of population, urbanization, and demands of building services and comfort levels, the sharp rise of building energy use is probably inevitable [1]. A useful measure to reduce building energy use is integrating solar energy technologies with building envelopes such as Building integrated photovoltaic (BIPV) or building attached photovoltaic (BAPV) systems [2].

It was predicted by the International Energy Agency (IEA) that building integrated solar PV technology which is considered during the design and construction of all types of buildings would be a future potential [3]. As it is revealed by a report conducted by IEA about the prospect of the building integrated PV systems (BIPV) in fourteen selected countries, a total potential BIPV area is around 23 billion m^2 which is able to generate about the electricity of 3 pWh annually [4]. It was concluded by

Oliver and Jackson that compared with the centralized PV plant, BIPV systems possess three main benefits [5]:

    (1) The need of the land, fence, access road and other important support components can be avoided, for the PV panels are attached or replacing the building structure. The most buildings are close to the electricity grid which means that some cabling cost can also be avoided.

    (2) When the electricity is generated by the BIPV systems, it will be consumed by buildings themselves, therefore the losses that caused by the transmission and distribution of the electricity can be minimized. As for the commercial buildings, their electricity demands coincide with the peak electricity generation from BIPV systems.

    (3) The overall cost of the BIPV system can be further reduced due to the substitution parts of the building roof, window and façade.

In the recent years, researchers have realized the advantages of introducing the concentrating PV (CPV) into the BIPV systems as BICPV (Building Integrated Concentrating Photovoltaic), so the use of the concentrators have significantly increased in the last decades, such as sky lights, double glazing windows and solar blinds [6, 7]. 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 [3]. In this area, the compound parabolic concentrator (CPC) is proved to be a more utility and economic concentrator [8].

Since the concept of the CPV proposed for the BIPV systems, there are a lot of researchers have committed themselves in designing and integrating solar concentrators with buildings. Carlo Renno et al designed a concentration 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 [9]. Mallick et al designed a novel asymmetric CPC which consists of two different parabolas, and the simulation and experiment results showed that it is a feasible way to integrate it 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) [10, 11].

It has been proved by Xuan et al. [12] and Li et al. [13] that asymmetric compound parabolic concentrator shows the promising concept of introducing the BICPV systems for building south wall integration. Based on the lens-walled structure, a novel asymmetric compound concentrator (ACPC) by adopting the rotation angle for the reflection lens-walled structure to increase the overall acceptance range is proposed in the paper. An optical model is built for the ACPC by the software Lighttools. The indoor experiments are conducted to study the optical and electrical performance of the ACPC-PV.

2. The geometric structure of the asymmetric compound parabolic concentrator (ACPC)

The lens structure of the asymmetric compound parabolic concentrator is shown in Fig.1, which consists of the asymmetric compound parabolic curves AB and CD. The equations of AB and CD are expressed in Eqn. (1) and (2). In order to increase the energy collection for the asymmetric concentrator by enlarging the front aperture, the parabolic curve AB is rotated by the lower end point B for a certain degree of 15°, then the curves of the $A'B$ and CD will be the outer contour of the ACPC. Finally, $A'B$ and CD are rotated by the up end points A' and C with the specific angle (usually 3-5°) to form the lens-walled structure for the ACPC. Considering the machining precision, the upper part of the ACPC are truncated at EF and GH to make it easier to manufacture. The geometric concentration ratio of the ACPC is 2.4X, according to the equation: EH / BD, the distance between $B'D'$ and BD is the base height of the ACPC.

$$-0.4x + 0.917y + 5.007 = \frac{1}{28}\left(0.917x + 0.4y + 4.585\right)^2 \quad 5 \le x \le 6 \tag{1}$$

$$-0.830x + 0.550y + 4.980 = \frac{1}{36.67}(0.55x + 0.83y + 2.756)^2 \quad 5 \le x \le 12.5 \tag{2}$$

According to Snell's law, the lens-walled structure of the ACPC can make use of the total internal reflection to collect sun rays. For this reason, the solar energy usage ratio can be increased obviously. Thus the lens-walled structure can achieve the same function as the dielectric compound parabolic concentrator but less material needed. However, due to the restriction of the incidence angle, not every sun ray can be collected through the total internal reflection, which will escape the concentrator. In order to collect the escape sun rays, an asymmetric mirror CPC is also integrated with the lens-walled structure to form as the ACPC, the geometric figure of which is shown in Fig. 2. In this way, the sun rays at various incidence angles can be collected through either the total internal reflection or the specular reflection.
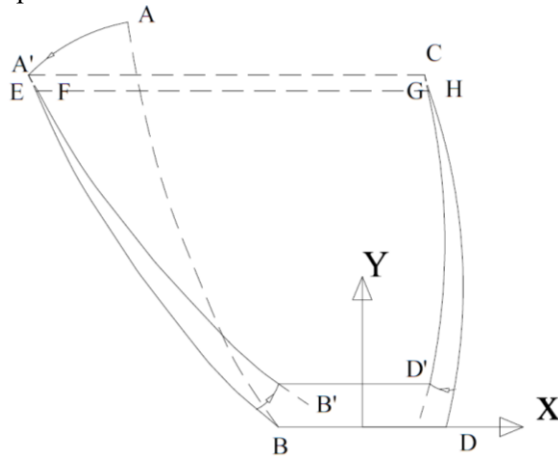

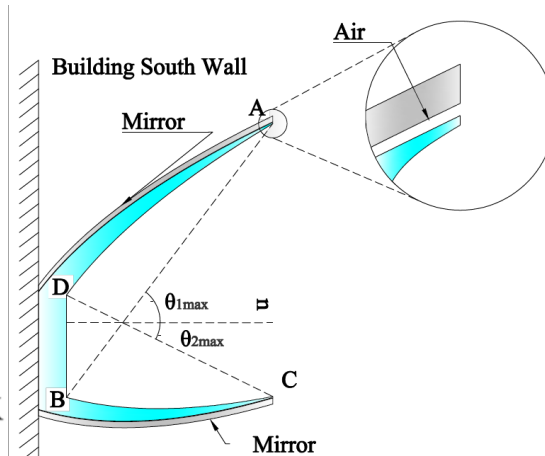Figure 1 Formation process diagram of the lens-walled structure.

Figure 2 The structure of the ACPC.

3. Ray-tracing simulation and experimental investigation

The model of the ACPC is first designed in the SolidWorks and then transferred into Lighttools for the optical simulation. The optical efficiencies of the ACPC at different incidence angles are then determined. Lighttools is a fast and accurate ray-tracing photometric analysis program which provides the optical system modeling and performance evaluation for non-imaging optical design [12].

For the optical simulation, the PMMA is chosen as the material of the concentrator and the specular reflectivity is set as 90%. The light source generates a solar intensity of 1000Wm^{-2} with 10000 solar rays which are assumed to be parallel.

The prototype of the ACPC is manufactured by the CNC wire-cutting machine. The mirror reflectors are gotten from the evaporated aluminum coating, and a reflectivity of around 85% is achieved for the reflection mirrors. Photographs of the concentrator are presented in Fig. 3. Considering the machining precision, finally the ACPC prototype with the geometrical concentration of 2.3X is got, the total height, aperture width, length and absorber width of which are 22.8 mm, 34.5 mm, 70 mm and 15 mm respectively.

In the indoor experiment, a solar simulator (Oriel Sol3A Model 90943A) from Newport Corporation is adopted to generate a ray intensity of 1000 W/m^2 through a 450W Xenon lamp. The electrical characteristics of solar cells are derived with a Keithley 2420 digital source meter (Keithley, USA). The room temperature is kept at a constant value of 25℃ during the entire test period. The ray intensity of the solar simulator is calibrated by the PV reference system before the experiment test and in order to avoid the unpredictable influence of other light rays, the experiment is conducted in a dark environment.

4. Results and discussion

4.1 simulation results

The base height of the ACPC plays a vital role in the optical performance for it can influence the ray path near the base area. Based on the optical model built through the SolidWorks and Lighttools, the effect of the base height on the optical performance of the ACPC can be investigated. Detailed simulation results are presented in Fig. 4. From the results, it can be seen clearly that with the base

height increases form 1.35 mm to 5 mm, the optical efficiency of the ACPC always shows a decreasing trend. With the base heights of 1.35-5 mm, the optical efficiency remains at high level while when the base height is larger than 2.35 mm, the optical efficiency decreases significantly. Considering the cost, weight and machine precise, the base height of 2.35 mm is a better choice. Thus, the ACPC with the base height of 2.35 mm will be detailed studied in the paper.
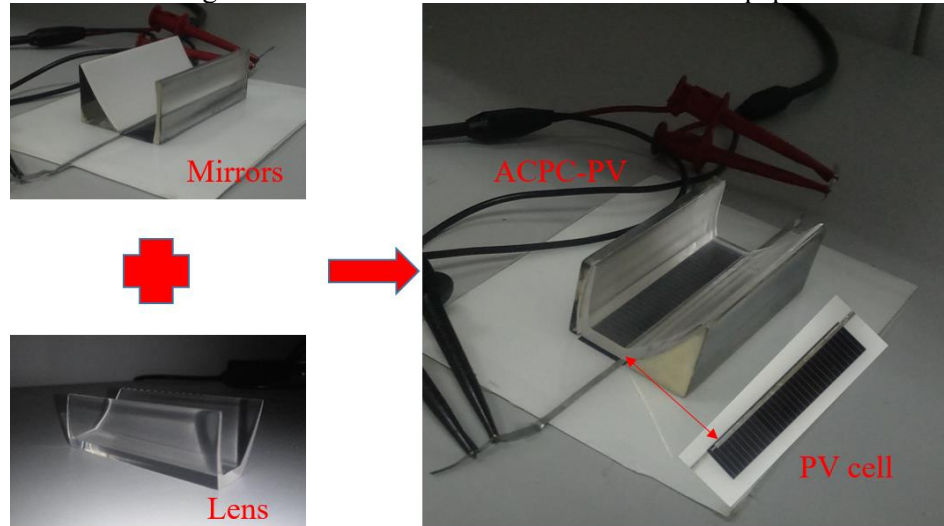

Figure 3 The prototype of the ACPC.

4.2 Indoor experiment results

For the actual engineering, the angular response of the ACPC-PV is very important because the solar incidence angles on the building south wall varies a lot throughout the year. In the following section, the electrical and optical performance of the ACPC-PV at the various incidence angles as compared with the non-concentrating PV are detailed analyzed.

The short-circuit current of the ACPC-PV and the bare cell at the incidence angles of 0°-65° are presented in Fig. 5. From the results, it can be seen clearly that the short-circuit current of the ACPC-PV and the bare cell all shows a decreasing trend as the incidence angle increases, which is mainly caused by the cosine effect [14]. It should be noted that during the experiments, the ACPC-PV and PV are titled from 0°-65° to create different incidence angles instead of titling the solar simulator. Thus as the title angle increases, the actual solar intensity on the front aperture will decrease which makes the short-circuit current decrease. But it's obvious that the short-circuit current produced by the ACPC-PV are always much larger than that produced by the bare cell within the incidence angles of 0°-65°.

The opto-electronic gain and the optical efficiency of the concentrator can both be used to identify the optical performance of a concentrator. The opto-electronic gain of a concentrator is defined as the ratio of the short-circuit current of the CPV module to that of the bare cell [3, 15]. The optical efficiency of the concentrator is the ratio of the solar radiation captured by the absorber of the concentrator to the total incoming solar radiation through the aperture of the concentrator and it can also be got by dividing the opto-electric gain by the geometric concentration ratio of the concentrator [16]. The maximum acceptance angle of a concentrator is defined as the angle when the gain reaches 90% of its peak value [17]. It has been proved that the short-circuit current is proportional to the solar radiation that falls on the PV, thus the actual optical efficiency of the ACPC can be expressed by:

$$\eta_{\mathrm{opt,ac}} = \frac{1}{C} \frac{I_{sc}^{with}}{I_{sc}^{without}} \tag{3}$$

Where $\eta_{\mathrm{opt,ac}}$ is the actual optical efficiency of the concentrator; C is the geometric concentration ratio of the concentrator; I_{sc}^{with} is the short circuit current of the concentrating PV; $I_{sc}^{without}$ is the short circuit of the non-concentrating PV. The opto-electronic gain and the optical efficiency of the ACPC are presented in Fig. 6 and Fig. 7 respectively.
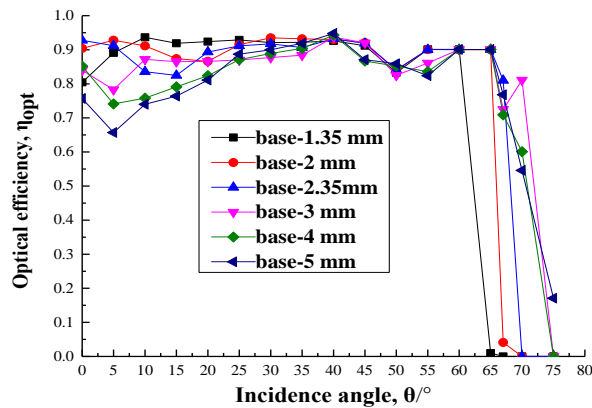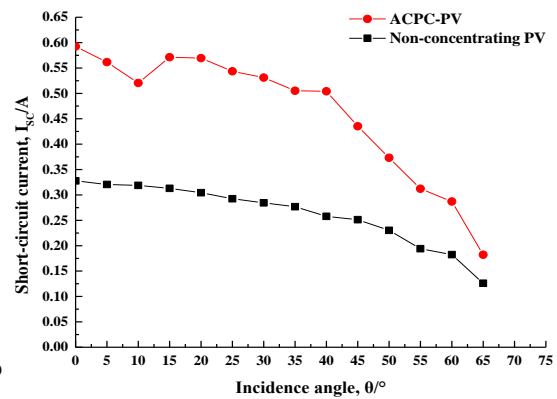
Figure 4 The effect of the base height.

Figure 5 The short circuit current variation of the ACPC-PV and the bare cell at different incident angles.

It can be seen clearly from the results in Fig. 6, the opto-electronic gain of the ACPC-PV are all larger than 90% of the peak value within the incidence angles of 0°-65°. So it can be concluded that the acceptance range of ACPC is 0°-65°, which shows a good building south wall integration potential. And the average value of the optp-electronic gain of the ACPC within the acceptance range is around 1.74. The simulation results are also presented in Fig. 6. A similar trend of the experiment results is observed as the simulation results and they show a good agreement.

The simulation and actual optical efficiency of the ACPC at various incidence angles are shown in Fig. 7. From the results, it can be seen clearly that the experiment and simulation results show a good agreement with an average deviation of around 13%. The main reasons that cause the deviation can be concluded as [17]: 1) Manufacturing errors which makes the surfaces of the ACPC flawed; 2) the deviation of the ACPC and the PV cell. When soldering the ACPC on the PV cell base, assembly errors existed. 3) Test errors.
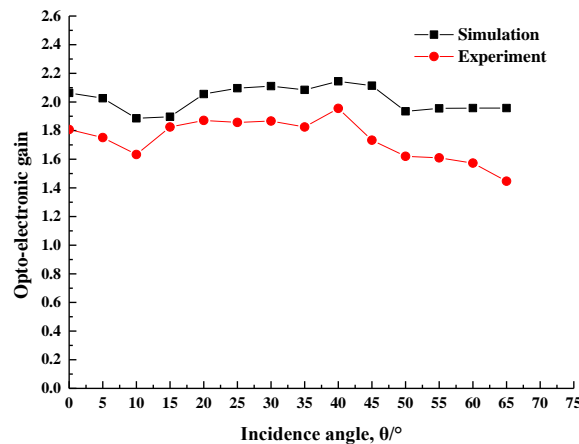

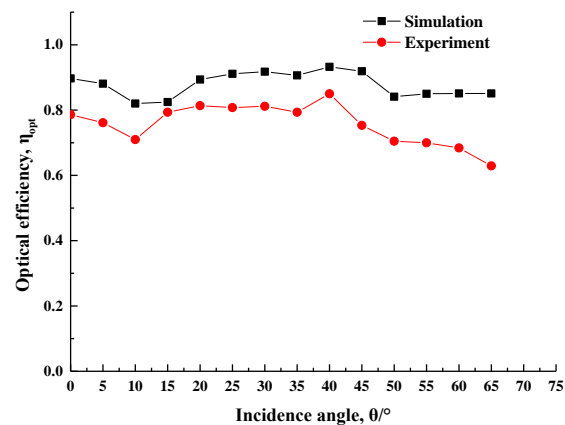Figure 6 The opto-electronic gain of the ACPC at different incidence angles.

Figure 7 The optical efficiency of the ACPC at different incidence angles.

5   Conclusion

A novel asymmetric compound parabolic concentrator (ACPC) is proposed in this paper for building south wall integration. The optical model is built in the software Lighttools to study the optical performance of the ACPC and optimize the geometric parameters of it. The indoor experiment under a solar simulator is also conducted to analyze the actual electrical performance of it. A good agreement is observed between the experiment and simulation results. The ratio of the maximum power gotten from the ACPC-PV to that produced by the non-concentrating PV cell delivers an average concentration ratio of 1.74X at various incidence angles which is around 75.7% of the maximum theoretical geometric concentration ratio of the designed ACPC. The average deviation of the experiment results from the ray tracing results is around 13% due to manufacturing errors,

mismatch losses, series resistance losses, etc. Through the opto-electronic gain analysis, the acceptance range of the ACPC can be determined as 0°-65° with high optical efficiency (average values of 75.7% for the experiment and 87.8% for the simulation) that it shows a good potential as a static concentrator for building south wall integration.

References:
[1]   Omer AM 2008 Energy, environment and sustainable development *Renewable and Sustainable Energy Reviews* **12** 2265-2300.
[2]   Chow TT, He W and Ji J 2007 An experimental study of façade-integrated photovoltaic/water-heating system *Applied Thermal Engineering* **27** 37-45.
[3]   Muhammad-Sukki F, Abu-Bakar SH, Ramirez-Iniguez R, McMeekin SG, Stewart BG and Sarmah N 2014 Mirror symmetrical dielectric totally internally reflecting concentrator for building integrated photovoltaic systems *Applied Energy* **113** 32-40.
[4]   International Energy Agency (IEA), 2002. Potential for building integrated photovoltaics. Report IEA-PVPS T7-4:2002 (Summary), IEA.
[5]   Oliver M and Jackson T 2001 Energy and economic evaluation of building-integrated photovoltaics *Energy* **26** 431-439.
[6]   Sellami N, Mallick TK and McNeil DA 2012 Optical characterisation of 3-D static solar concentrator *Energy Conversion and Management* **64** 579-586.
[7]   Norton B, Eames PC, Mallick TK, Huang MJ, McCormack SJ and Mondol JD 2011 Enhancing the performance of building integrated photovoltaics *Solar Energy* **85** 1629-1664.
[8]   Qiushi Wang, Ziye Zhu, Gang Wu, Xiang Zhang and Hongfei Zheng 2018 Energy analysis and experimental verification of a solar freshwater self-produced ecological film floating on the sea *Applied Energy* 224: 510-526.
[9]   Renno C and Petito F 2013 Design and modeling of a concentrating photovoltaic thermal (CPV/T) system for a domestic application *Energy and Buildings* **62** 392-402.
[10]   Mallick TK, Eames PC, Hyde TJ and Norton B 2004 The design and experimental characterisation of an asymmetric compound parabolic photovoltaic concentrator for building fa?ade integration in the UK *Solar Energy* **77** 319-327.
[11]   Mallick T and Eames P 2007 Design and fabrication of low concentrating second generation PRIDE concentrator *Solar Energy Materials and Solar Cells* **91** 597-608.
[12]   Xuan Q, Li G, Pei G, Su Y and Ji J 2017 Design and Optical Evaluation of a Novel Asymmetric Lens-Walled Compound Parabolic Concentrator (ALCPC) Integration with Building South Wall *Journal of Daylighting* **4** 26-36.
[13]   Li G, Xuan Q, Lu Y, Pei G, Su Y and Ji J 2018 Numerical and lab experiment study of a novel concentrating PV with uniform flux distribution *Solar Energy Materials and Solar Cells* **179** 1-9.
[14]   Sarmah N, Richards BS and Mallick TK 2014 Design, development and indoor performance analysis of a low concentrating dielectric photovoltaic module *Solar Energy* **103** 390-401.
[15]   Ning X, Winston R and O'Gallagher J 1987 Dielectric totally internally reflecting concentrators. *Applied Optics* **26** 300-305.
[16]   Buonomano A, Calise F, Dentice D'Accadia M and Vanoli L 2013 A novel solar trigeneration system based on concentrating photovoltaic/thermal collectors. Part 1: Design and simulation model *Energy* 2013 **61** 59-71.
[17]   Mammo ED, Sellami N and Mallick TK 2013 Performance analysis of a reflective 3D crossed compound parabolic concentrating photovoltaic system for building façade integration *Progress in Photovoltaics: Research and Applications* **21** 1905-1103.