Applied Energy 125 (2014) 21–27

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Design and investigation of a novel lens-walled compound parabolic concentrator with air gap

Li Guiqiang [a,b], Pei Gang [a,b,*], Su Yuehong [b], Wang Yunyun [a], Ji Jie [a,*]

[a] *Department of Thermal Science and Energy Engineering, University of Science and Technology of China, 96 Jinzhai Road, Hefei City 230026, China*
[b] *Institute of Sustainable Energy Technology, University of Nottingham, University Park, Nottingham NG7 2RD, UK*

HIGHLIGHTS

- The structure of the lens-walled CPC with air gap was described.
- Lens-walled CPC with air gap can increase above 10% of the optical efficiency.
- Flux distribution of lens-walled CPC with air gap was analyzed.
- The total internal reflection led to a high optical efficiency.

ARTICLE INFO

Article history:
Received 11 August 2013
Received in revised form 20 February 2014
Accepted 21 March 2014
Available online 12 April 2014

Keywords:
CPC
Lens-walled
Total internal reflection
Air gap
BICPV

ABSTRACT

Stationary solar concentrators can be integrated with building façade and roof, which can reduce the area of solar cells and attain higher temperature heat resource, especially in winter for building application. In this paper, a stationary lens-walled compound parabolic concentrator (CPC) with air gap was designed and investigated to meet the application requirements. The lens-walled CPC with air gap differs from the original lens-walled CPC in that it has an air gap between the lens structure and the reflector that maximizes total internal reflection and improves optical efficiency by reducing the optical losses of the specular reflection. The simulation and experiment verified the function of the new structure, and the results indicated that the lens-walled CPC with air gap increases optical efficiency by more than 10% compared with the original lens-walled CPC. In addition, the flux distribution of the lens-walled CPC with air gap is more uniform than that of the common mirror CPC. Thus, the lens-walled CPC with air gap not only has a larger half acceptance angle and a more uniform flux distribution than the common mirror CPC but also operates at a higher optical efficiency than the original lens-walled CPC. Thus, the lens-walled CPC with air gap provides a realistic and valid solution to Building Integrated with Concentrating Photovoltaic (BICPV) as a stationary concentrator and has good prospects for several applications.

1. Introduction

With the increase of building energy consumption, solar energy as an inexhaustible clean energy, in combination with the building, is one of the effective measures of building saving energy. The need besides of electricity and hot water, also includes building heating, refrigeration, dehumidification, which require higher quality heat source, especially in winter. Building Integrated with Concentrating Photovoltaic/Thermal (BICPV/T) can to some extent meet these requirements. The production of concentrating photovoltaic (CPV) has seen a rapid increase [1]. CPV system can offer a host of advantages over conventional flat panel devices, such as a higher electrical conversion efficiency in the PV cells, better use of space, ease of recycling of constituent materials, and reduced use of toxic products involved in the PV cells' production process. Broad prospects for application are available for Building Integrated Concentrating Photovoltaic (BICPV). The saving cost of PV for a CPV system with a low concentration ratio is not significant with the decreasing PV price. BICPV provides additional advantages to the common CPV advantages: First, the concentrator materials used in large-scale manufacturing processes are still cheaper than the solar cell materials [2], and the cost is further lowered if the concentrator materials are used to replace structural elements. The Mont-Cenis Academy (Fig. 1) in Herne, Germany, is a notable example of Building Integrated with Photovoltaic (BIPV) being integrated into

---

* Corresponding authors. Address: Department of Thermal Science and Energy Engineering, University of Science and Technology of China, 96 Jinzhai Road, Hefei City 230026, China (P. Gang). Tel./fax: +86 551 63607367.

E-mail addresses: peigang@ustc.edu.cn (P. Gang), jijie@ustc.edu.cn (J. Jie).

http://dx.doi.org/10.1016/j.apenergy.2014.03.042
0306-2619/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature

BIPV	Building Integrated with Photovoltaic
BICPV	Building Integrated with Concentrating Photovoltaic
CPV	concentrating photovoltaic
C_g	geometrical concentration ratio
I_{sc}^{with}	short-circuit current of concentrating PV
$I_{sc}^{without}$	short-circuit current of PV without a concentrator
η_{opt}	optical efficiency
$\theta_{\max}$	half acceptance angle

semi-transparent facades. The project produces 650,000 KW h annually with 10,500 m^2 of solar cells. However, the project cost could have been reduced by reducing the large surface area by at least 50% and replacing the solar cells with cheaper concentrator material by employing CPV systems [3–5]. Second, the combination of BICPV and thermal application for the building would result in a heat resource that produces higher temperatures than flat plat PV/T [6], increasing the prospects of solar energy use in buildings especially during the winter season.

In practical application, stationary solar concentrators are more suitable for BICPV application, which can be designed for fixed one-time installations without being restricted by the tracking and controlling system and thus minimize costs. Thus, BICPV can compete with the standard flat plat PV. However, stationary solar concentrators also have certain disadvantages: Firstly, the acceptance angle is limited by the absence of a solar tracking system during fixed installation. Secondly, the acceptance angle and geometrical concentration ratio are inversely proportional. When the acceptance angle is large, the geometrical concentration ratio is relatively low, decreasing the high concentration. Researches have been done on numerous stationary concentrators to widen their acceptance angles based on certain geometrical concentration ratios. Uematsu et al. [7] designed flat-plat static-concentrator photovoltaic modules. Mallick et al. [2,8] made a series of investigations into asymmetric compound parabolic concentrating building facade integrated photovoltaics. Yoshioka et al. [9] evaluated the performance of two-dimensional compound elliptic lens concentrators against a yearly distributed insolation model. Maruyama et al. [10] studied the wedge-shaped static solar concentrator by using total internal reflection. Sellami and Mallick [11] made the optical efficiency study of PV crossed compound parabolic concentrator. Muhammad-Sukki et al. [12,13] presented a mirror symmetrical dielectric totally internally reflecting concentrator for building integrated photovoltaic systems. Su et al. [14] and Li et al. [15] made a preliminary simulation and verified via a comparison experiment that with a certain concentration ratio, the half acceptance angle of a lens-walled compound parabolic concentrator (CPC) can be widened.

Fig. 1. Multi-purpose building of Mont-Cenis Academy in Herne, Germany.

A significant issue for CPV and BICPV is the concentrating solar cells' non-uniform flux distribution, which causes hot spots and current mismatch, thereby decreasing PV efficiency and service life [16–20]. The parameters affected by the reduction of solar cell performance as a result of non-uniform flux distribution include (a) total photocurrent, (b) the cell's short-circuit current, (c) the cell's short-circuit current density, (d) average illumination intensity, (e) open-circuit voltage, and (f) fill factor [16]. CPC is a common solar concentrator with non-uniform flux distribution. Although several researchers have investigated higher optical efficiency by amplifying the half acceptance angle of the CPC with the use of dielectric materials [21–24], the refraction only modified the incidence angle and failed to significantly improve the absorber's flux distribution.

The lens-walled CPC improves the flux distribution of a mirror CPC [25] and has a larger half acceptance angle as a stationary solar concentrator, which is suited to BICPV. However, the original lens-walled CPC has a lower optical efficiency because of multiple specular reflections. In this study, a novel lens-walled CPC with air gap is designed to improve optical efficiency as compared with the original lens-walled CPC and the common CPC. The experiment verified the increased optical efficiency, greater half acceptance angle, and improved flux distribution of the lens-walled CPC with air gap, which would increase the optical efficiency 10% higher than the original lens-walled CPC for BICPV.

2. Design principle

According to [14], the outside surface of the original lens-walled CPC is directly coated. The refraction on the lens structure changes the sunlight's incidence angle direction, showing that the original lens-walled CPC has a greater half acceptance angle than the common mirror CPC at the same geometrical concentration ratio. As shown in Fig. 2, the optical efficiency of the original lens-walled CPC is lowered because of the optical losses as a result of the multiple specular reflections experienced by the lights prior to reaching the base of the original lens-walled CPC. If the original lens-walled CPC was not coated directly, total internal reflection occurs on the outside surface since the incidence angles of parts of the light may be greater than the critical angle on the outside surface.

To reduce the optical losses resulting from specular reflection and maximize the total internal reflection, a novel lens-walled CPC with air gap was proposed. The CPC structure is shown in Fig. 3. The lens structure of the lens-walled CPC with air gap is similar to that of the original lens-walled CPC. To form a new CPC, the cross-sectional parabolic curves of a common CPC are rotated around their top end points, pointing inward to a degree of 3°. The area between the original CPC and the new CPC curves is then filled with a dielectric material (e.g., acrylic material) to form a lens. The original lens was not directly coated; thus, coating was added to a common mirror CPC to form the lens-walled CPC with air gap. The optical path of the lens-walled CPC with air gap is shown in Fig. 4. When the actual incidence angle is greater than the critical angle, light does not pass through the outside lens surface but is reflected directly because of the total internal reflection. When the incidence angle is smaller than the critical angle, light passes through the air gap and is reflected back by the mirror reflector.