PARAMETRIC STUDY OF SOALR CONCENTRATOR COMPOSED OF A FLAT FRENSEL LENS AND A REFLECTIVE SECONDARY OPTICAL ELEMENT

Yi-Cheng Chen[1,2], Wan-Yi Hsu[1], Yu-Hsuan Lin[1] and Chia-Hsun Su[2]

[1] Department of Mechanical Engineering, National Central University, Jhongli, Taoyuan (Taiwan)

[2] Institute of Opto-Mechatronics Engineering, National Central University, Jhongli, Taoyuan (Taiwan)

1. Abstract

This study presents a parametric design process of a solar concentrator for high concentrated photovoltaic (HCPV) system. The concentrator comprises a flat Fresnel lens and a reflective secondary optical element (SOE). Ray tracing simulation is utilized to explore the optical performance of the concentrator under various design parameters. The optical performance of the solar concentrator, including the optical efficiency, acceptance angle and irradiance distribution, is evaluated via parametric study to achieve an optimum design. Finally, the achieved design of the solar concentrator for HCPV exhibits a high optical concentration ratio (OCR) of 909X, and an acceptance angle of 1.03°.

2. Introduction

Nowadays, the interests on solar energy boost due to the increasing demand of renewable energy Concentrated photovoltaic (CPV) systems apply solar concentrators to collect sun energy from a large area into a relatively small solar cell. The solar cells used in CPV systems are usually III-V cells, which exhibit higher efficiency and higher cost compared with Si cells. The geometric concentration ratio (GCR) is generally defined as ratio of the area of sun collected to the area of the cell (Winston et al., 2005; Luque and Andreev, 2007). A CPV system is usually classified as a high CPV (HCPV) if its GCR is higher than 300X. Various types of primary concentrating elements are used in different CPV systems, such as refractive type (typically using a Fresnel lens), reflective type (typically using a parabolic mirror), and double-reflectors type (typically using a parabolic primary mirror and a hyperbolic secondary mirror), etc (; Leutz et al., 1999; Lin et al., 2005; Victoria et al., 2009).

Since using a concentrating element alone may result in serious problems of localized hot spots and poor uniformity, practically an SOE is adopted in a CPV system. Localized hot spots and poor uniformity will deteriorate not only the efficiency of the CPV system but also the service life of the cells. Various researchers have study the suitable SOE designs for individual CPV system (Jaus et al., 2008; Jaus et al., 2009; Ning et al., 1987; Andreev et al., 2008).

The general goal of a concentrator design is to attain a good optical efficiency η (over 70%) and a wide acceptance angle (beyond $\pm 1^{\circ}$). The acceptance angle $\theta_{90\%}$ is commonly defined as the incidence angle corresponding to 90% of the maximum optical efficiency η at normal incidence (Victoria et al., 2009; Andreev et al., 2008). Moreover, solar concentrators are generally characterized by the optical concentration ratio (OCR). The OCR is defined as the multiplication GCR C and the optical efficiency η (Leutz et al., 1999; Lin et al., 2005)

$$Optical\ Concentration\ Ratio\ =\ C \times \eta \quad \text{(eq. 1)}$$

This study focuses on the optimum design of reflective SOE for a flat Fresnel lens. Ray tracing technique is adopted to evaluate the optical performance of the refractive solar concentrator with different design parameters of SOE. Finally, an optimization of reflective pyramid-type SOE is presented, and the effects of incidence angle on the optical efficiency and irradiance distribution on the cell are also discussed.

3. Design of Solar Concentrator

3.1. Design of Fresnel Lens

The solar concentrator is composed of a flat Fresnel lens and a reflective SOE of truncated pyramid shape.

After parametric analysis of the design parameters of the flat Fresnel, the basic parameters of the Fresnel lens are determined as follows: the size is 165mmx165mm, the focal length is 200mm, and the f/number is 1.21. The initial size of the receiver, i.e. the solar cell, is given as 7mmx7mm, thus the initial geometric concentration ratio (GCR) is 555X. The initial position of the receiver is placed at the focal plane of the Fresnel lens, i.e. 200mm beyond the concentrating lens. The material of the Fresnel lens is chosen as common optical plastic, PMMA (PolyMethyl Methacrylate), and its nominal refractive index is 1.491 at 550nm. The optical performance of the solar concentrator is analyzed by ray-tracing technique with a commercial optical simulation package.

The initial simulation is based on single wavelength of 550nm to save computation complexity without loss of simulation accuracy. Firstly, the effect of prism pitch of the Fresnel lens on the optical efficiency is analyzed and the results are summarized in Fig.1. The optical efficiency is almost the same when the prism pitch is between 0.4mm~3mm. However, a rapid decline of the optical efficiency is observed in Fig.1 when the prism pitch is larger than 3mm. Notably, a finer prism pitch will increase the manufacturing complexity and the cost of the Fresnel lens. Thus a prism pitch of 1.2mm is selected for the Fresnel lens in this study.

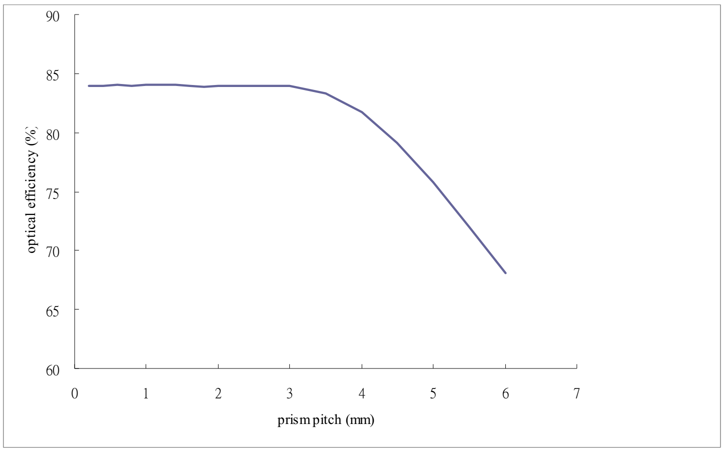

Fig. 1: Optical efficiency of the flat Fresnel lens under different prism pitches.

The optical efficiencies of the solar concentrator composed of the Fresnel lens alone under different incidence angles are analyzed and illustrated in Fig.2. A poor acceptance angle $\theta_{90\%}$ of 0.53° is observed and the corresponding optical efficiency is about 75.6%. The poor acceptance angle indicates that an SOE is needed to enhance the acceptance angle.

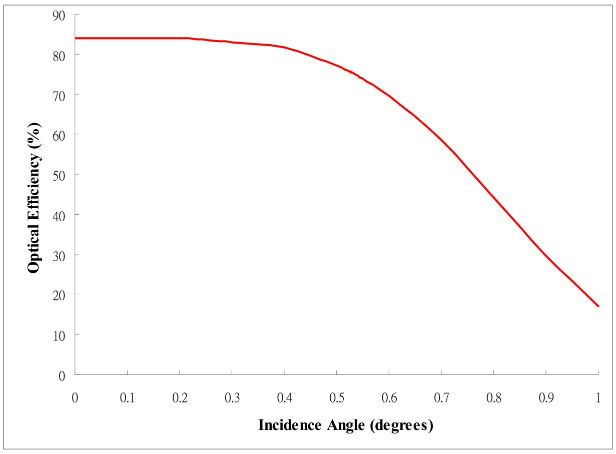

Fig. 2: Optical efficiency of the flat Fresnel lens under different incidence angles.

3.2. Design of Secondary Optical Element

An SOE is generally tailored with a concentrating lens to improve the acceptance angle as well as the irradiance uniformity on the solar cell. Systematical approach is applied to determine an optimum parameter set for the solar concentrator, including parameters of the flat Fresnel lens, the cell size, and the SOE. Finally, an optimum design parameter set of the solar concentrator is achieved, and the details are introduced in the following.

Figure 3 depicts the new design of the solar concentrator composed of a Fresnel lens and a tailored SOE of reflective pyramid-type. In this design, the cell size is reduced from 7mmX7mm to 5mmX5mm. Besides, the cell is moved 7mm forward from the focal plane of the concentrating Fresnel lens. Moreover, Fig.4 shows the SOE of truncated pyramid shape, and the basic design parameters of the SOE are height H, opening width W of the upper side, and the inclination angle of the walls α. The width of the lower side is designated as the same as the solar cell, i.e., 5mm in this design.

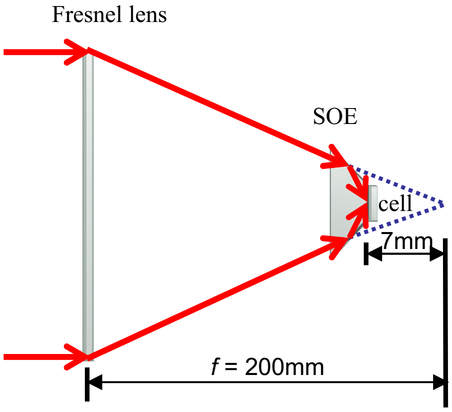

Fig. 3: Schematic diagram of the solar concentrator composed of a flat Fresnel lens and a reflective SOE.

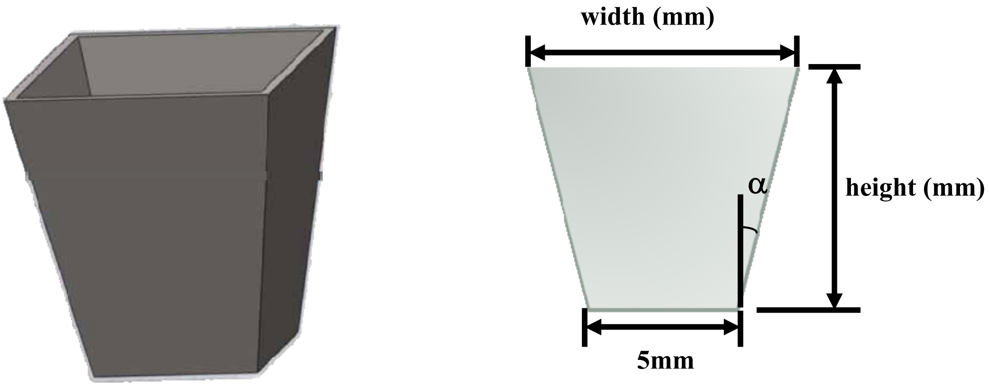

Fig. 4: Design parameters of the reflective SOE of truncated pyramid shape.

A series of parametric study has been performed to determine the optimum design parameters of the pyramid-shaped SOE. Referring to Fig.4, the relationship between the three parameters of the SOE can be easily expressed as follows

$$\alpha = tan^{-1}(\frac{W-5}{2H}) \quad \text{(eq. 2)}$$

Therefore, there are only two independent parameters of SOE. In the following simulation, the design parameters of the SOE considered in the simulation process are height, H, and inclination angle of the wall, α.The simulation results are performed by considering a single-wavelength of 550nm first, saving the computational efforts while not losing the simulation accuracy. Figure 5 and Fig.6 summarize the optical efficiencies under variations of the design parameters, W and α, of the SOE when the incidence angles are 0^o and 1^o, respectively. According to the results shown in Fig.5 and Fig.6, the optimum design parameters of the

SOE are selected as H=70mm and W=65 (the corresponding inclination angle $\alpha=23.2^{o}$), subject to constraints including an acceptance angle $\theta_{90\%}$ larger than 1^{o} and a minimum volume (cost) of the SOE.

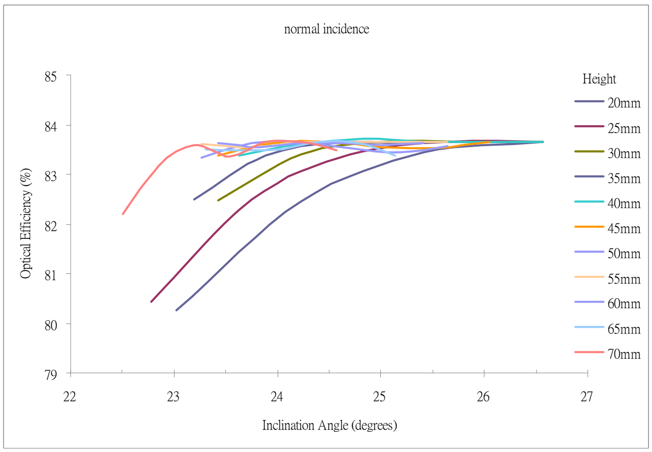

Fig. 5: Dependency of the optical efficiencies on design parameters of SOE when the incidence angle is 0^{o}.

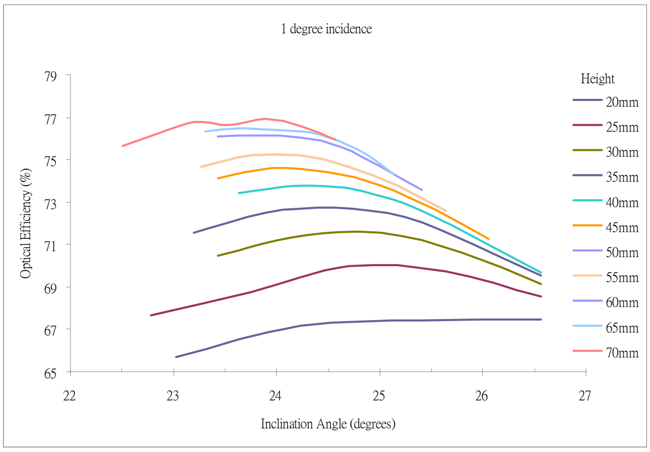

Fig. 6: Dependency of the optical efficiencies on design parameters of SOE when the incidence angle is 1^{o}.

The performance of the designed solar concentrator is then simulated considering solar spectrum for more realistic results. Figure 7 illustrates the resulting optical efficiencies of the solar concentrator, composed of the flat Fresnel lens and the optimum SOE, under different incidence angles. As Fig.7 reveals, the optical efficiency under normal incidence is 83.5%. Moreover, the GCR and OCR are 1089X and 909X, respectively, resulting from a reduced cell size of 5mmx5mm. The acceptance angle $\theta_{90\%}$ of the optimum design is 1.03^{o}.

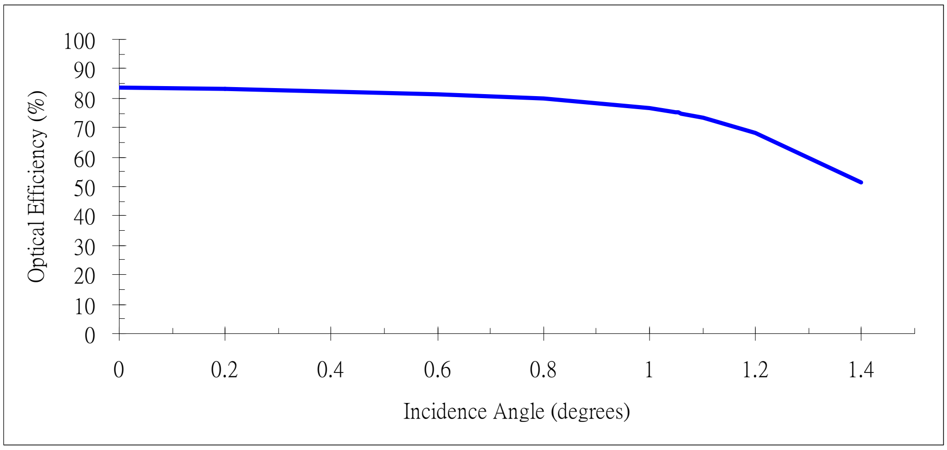

Fig. 7: Optical efficiency of the optimum solar concentrator design under various incidence angles.

4. Discussion

Table 1 summarizes the simulated results considering solar spectrum of the original design and optimum design of the solar concentrator under normal incidence, including GCR, OCR, acceptance angle $\theta_{90\%}$ and the optical efficiency. For the original design, the concentrator contains only the Fresnel lens and the cell size is 7mmx7mm. While for the optimum design, the concentrator comprises a Fresnel lens and an optimum reflective SOE of pyramid shape, and the cell is reduced to 5mmx5mm and its position is removed 7mm forward relative to the focal plane of the Fresnel lens. Under normal incidence, the OCR of the solar concentrator with an optimum pyramid SOE is 909X and the acceptance angle is improved to 1.03°. Furthermore, irradiance distribution of the optimum design is also discussed, and Fig.8 (a) and (b) illustrate the irradiance distribution on the solar cell under normal and 1 degree incidence angle, respectively.

Tab. 1: Comparisons of the optical performances of original and optimum concentrator design.

	Original Design	**Optimum Design**
GCR	555X	1089X
Optical Efficiency	83.84%	83.45%
OCR	465X	909X
Acceptance Angle $\theta_{90\%}$	0.47°	1.03°

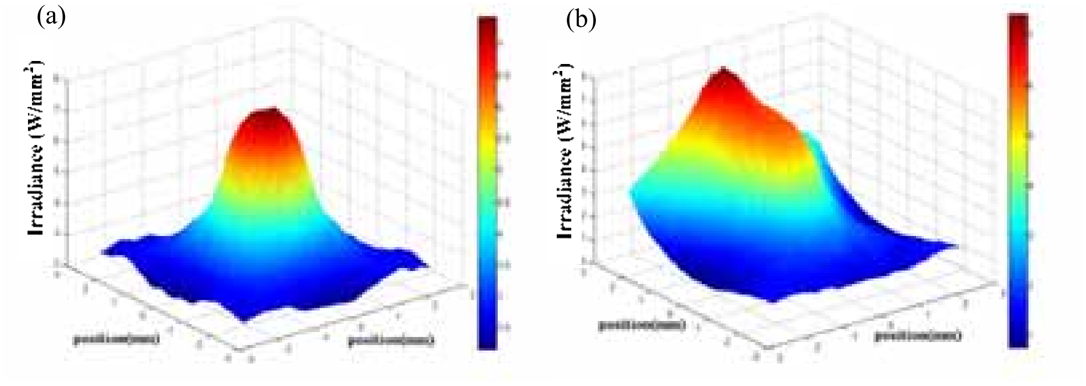

Fig. 8: Irradiance distribution on the cell under (a) Normal incidence (b) Incidence angle = 1°.

5. Conclusions

An optimum design of a solar concentrator composed of a flat Fresnel lens and an SOE is studied via parametric approach. Ray tracing technique enables us to estimate the optical performances of the solar concentrator under various design parameters. The optical efficiency of the optimum concentrator design is 83.5% under normal incidence considering solar spectrum. Besides, the OCR of the concentrator is 909X, and the optimized reflective pyramid-type SOE improves the acceptance angle $\theta_{90\%}$ to 1.03°. Irradiance distribution on the cell is also discussed and the uniformity may be further considered in the future optimization.

6. Acknowledgments

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7. References

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