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Optimal design of inverted truncated pyramid with Fresnel lens for concentrated photovoltaic Units

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Abstract. The aim of the presented work was to determine the optimum parameters of inverter truncated rectangular pyramid with Fresnel lenses. The use of secondary optical element (SOE) in a concentrated photovoltaic system can be effective in redirecting the sun light into the solar cell, increasing the concentration as well as improving the energy uniformity on the solar cell Ray tracing technique was used to simulate the optical characteristics of the CPV unit with various design parameters of the component. Finally, a typical concentrator was designed by using three possible materials, the Fused Silica, the BK7 and the PMMA.

1. Introduction

Concentrating photovoltaic (CPV) is becoming a promising option for clean energy use due to the reached high efficiencies in these photovoltaic systems. A CPV system is based on the combination of three components : receiver (solar cell), focusing optics and solar tracker. The focusing optics concentrate solar energy into a small surface solar cell, generally multijunction III-V based materials cells. This concentration can be done in one step: the sunbeam are directly routed to the cell via a primary optics, or in two steps, the rays are first focused on a secondary optical placed above the cell. Using a secondary optics has several objectives: increase concentration, homogenize the irradiance uniformity on the cell, and increase the acceptance angle of the module.

In terms of the primary optic, Fresnel lens and parabolic mirror are the best-known examples. But the availability of lenses on the market and their cost tend to impose them as the most used in current technologies [1]. Two methods are used to manufacture lenses, one using a type of plastic polymethyl methacrylate or PMMA [2] and the other the silicone-on-glass[3]. In the case of a system using a Fresnel lens, the chromatic aberration phenomenon causes nonuniformity of the concentrated distribution on the solar cell surface[4]. Localized hot spots and nonuniformity increase the cell temperature, cell resistance, and lower the efficiency. Secondary optics helps to solve this problem. Today there is some variety in design of secondary optics, which can be grouped into reflective and refractive optical elements of various forms. Refractive secondaries are more widespread, they consist of a transparent dielectric (glass or plastic) that redirects the beam at the cell. We can mention among other the compound parabolic concentrator (CPC), the refractive truncated pyramid (RTP), the dome, or the dielectric total internal reflector (DTIR) [5].

To improve the performance of CPV module, several work has been done. Ning et al. investigated the two-stage photovoltaic concentrators with Fresnel lenses as primaries and DTIR as secondaries. It was found that the two-stage concentrator offered increased acceptance angle, higher concentration and also a more uniform flux distribution than the Fresnel lens alone[6]. Andree et al. presented optimization of SOE for CPV unit with a flat Fresnel lens [7]. Furthermore Miñano et al. designed and manufactured a CPV system, which contained two optical elements a Fresnel lens and free form optics as secondaries) [8].

In this work we present a design of a secondary concentrator, the inverted truncated rectangular pyramid. The 3-D model of this design is established by TracePro and optimal parameters such as inclination angle and component height are determined with Fresnel lens. Optical efficiency, acceptance angle and irradiance distribution over the cell are also studied for three materials.

2. Design Process
A two-stage system consists of two optical components: a PMMA Fresnel lens as a primary optical element (POE) and a truncated rectangular pyramid as a secondary optical element (SOE). Figure 1 illustrates such a two-stage design. The POE has a diameter d of 350mm, a thickness of 3mm and a focal length f of 370mm. The taken size of the solar cell is 10 mm × 10 mm, and the theoretical geometric concentration ratio is 1225.

The Fresnel lens is characterized by its f_number, FN/# defined by: [9]

$$\mathrm{FN}/\# = \frac{\mathrm{f}}{\mathrm{d}} \quad (1)$$

$$\tan\,\theta = \frac{\mathrm{d}}{2\mathrm{f}} \quad (2)$$

θ is the semi-angle of the outco-mingbeam from the Fresnel lens

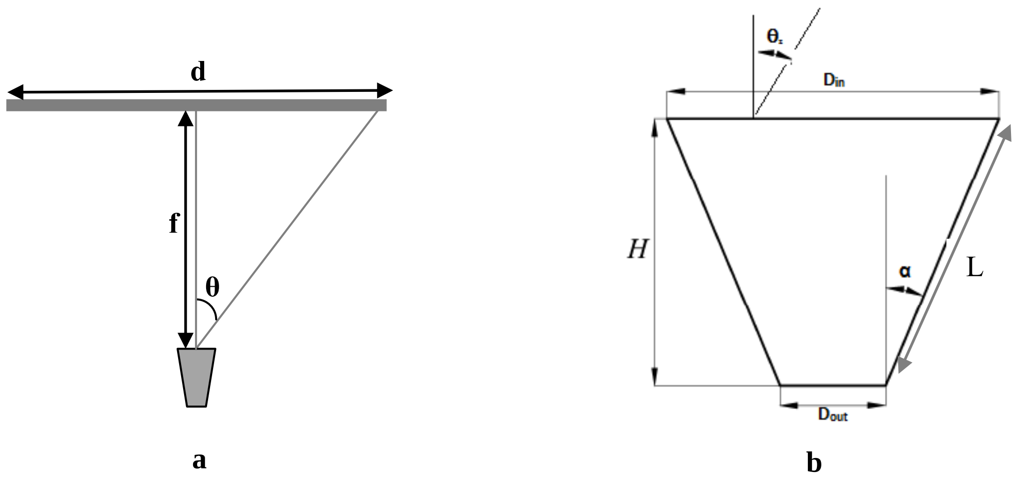

Figure 1. (a)two-stage concentrator (b)Design parameters of pyramid

The design of a concentrator involves some geometrical parameters. For instance the pyramid, shown in Fig.1 is characterized by the inclination angle α, the entrance aperture D_{in}, the exit aperture D_{out}, the slant length L , the height H and the angle between the vertical (normal incidence) and the incident light rayθ_z.

$$H = \frac{D_{in} - D_{out}}{2 \tan \alpha} \quad (3)$$

$$L = \frac{D_{in} - D_{out}}{2 \sin \alpha} \quad (4)$$

The required condition on the inclination angle and n the number of reflections for which the ray light reaches the exit aperture is as the following [10]:

$$2(n+1)\alpha + \theta_z \leq 90 \quad (5)$$

To minimize the losses, the incident light is allowed to experience no more than one total reflection in the SOE before reaching the cell. θ_z should be less than or equal to θ the incidence angle of Fresnel lens to effectively collect all the rays.

$$\theta_z \leq \theta \quad (6)$$

3. Simulation and results

3.1. Preliminary Design of the SOE

We suppose the initial value of inverted rectangular pyramid height H is 20mm. Since the exit aperture D_{out} is 10mm, the entry aperture D_{in} can be varied by changing the value of inclination angle α. considering the conditions cited before (equation (5) and equation (6)) α can be changed from 1° to 16°.The Fresnel lens is made by PMMA and The material used for SOE was BK7 glass. The incident light intensity on the Fresnel lens is set as 1000W/m^2. We simulated the system in TracePro software. Different optical properties and design parameters of the POE and SOE are mentioned in Table.1.

Table 1. Different parameters of CPV module

Title	value
Fresnel lens diameter	**350mm**
Focal length of Fresnel lens	**370mm**
Thickness of Fresnel lens	**3mm**
Material of Fresnel lens	**PMMA**
Material of the pyramid	**BK7**
Index of Refraction of BK7	**1.518**
Size of solar cell	**10mm x 10mm**
Light source	**1000W/m^2**

Figure 2 gives the evolution of the optical efficiency of the concentrator versus the inclination angle α. As we can notice, the optical efficiency increases with α, we reach86.4 % at 16°.

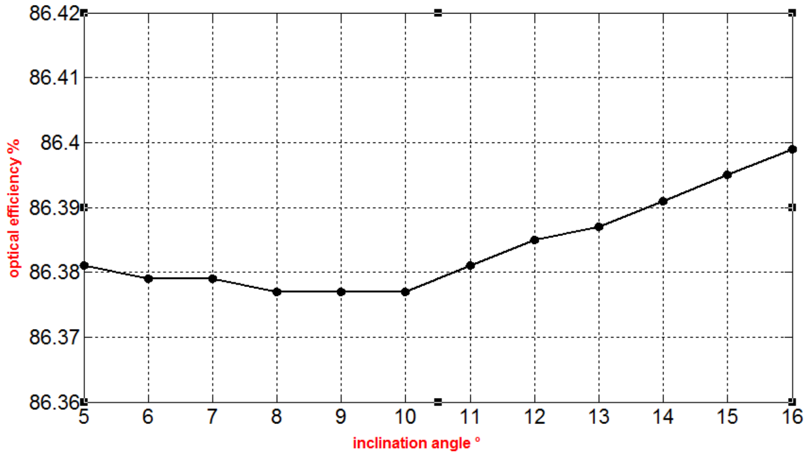

Figure 2. Optical efficiency of the Fresnel lens with pyramid

3.2. Optimization of the size of the pyramid, method 1

From simulation results we notice that the optical efficiency maximizes when α is set to 16°.So we fix D_{in}at 21,47mmthe corresponding value to α=16° and we vary the height value H from 15mm to 28mm and simulate the obtained system.
As shown in Figure 3 the optical efficiency decreases with an increase of the pyramid height. It is maximal when H is 15mm (86,50%).

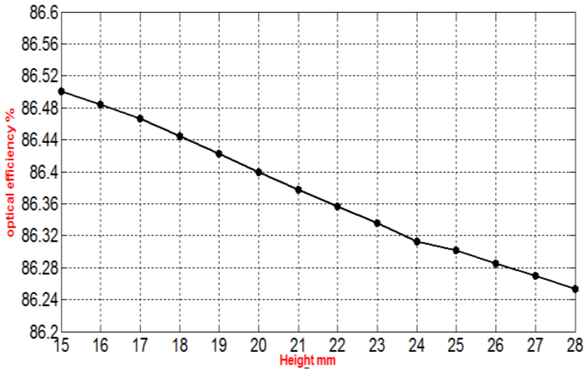

Figure 3. Optical efficiency versus height

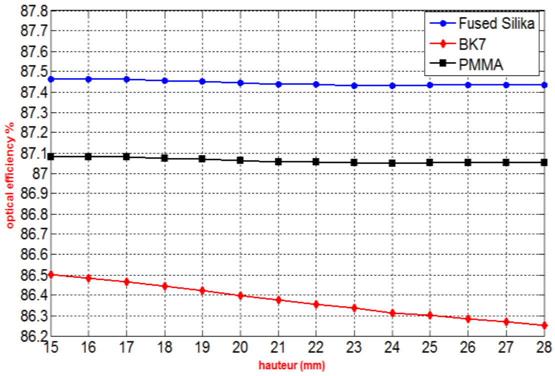

Figure 4. Optical efficiency versus height for three materials

We keep the same conditions and we simulate for two other materials: the PMMA and the Fused Silica. The refractive indexes of these materials are 1.493 and 1.46 respectively.
Figure 4 illustrates the effect of material on the optical efficiency. We can see that Fused Silica achieves a higher optical efficiency (87,462 %) than the PMMA(87,08 %) and BK7 (86,50 %).

3.3. Optimization of the size of the pyramid, method 2

As mentioned before two of the basic design parameters of the inverted truncated pyramid are the height H and the inclination angle α. To determine the optimum size of the pyramid a parametric design process with two values of H and various vales of α were performed [11].

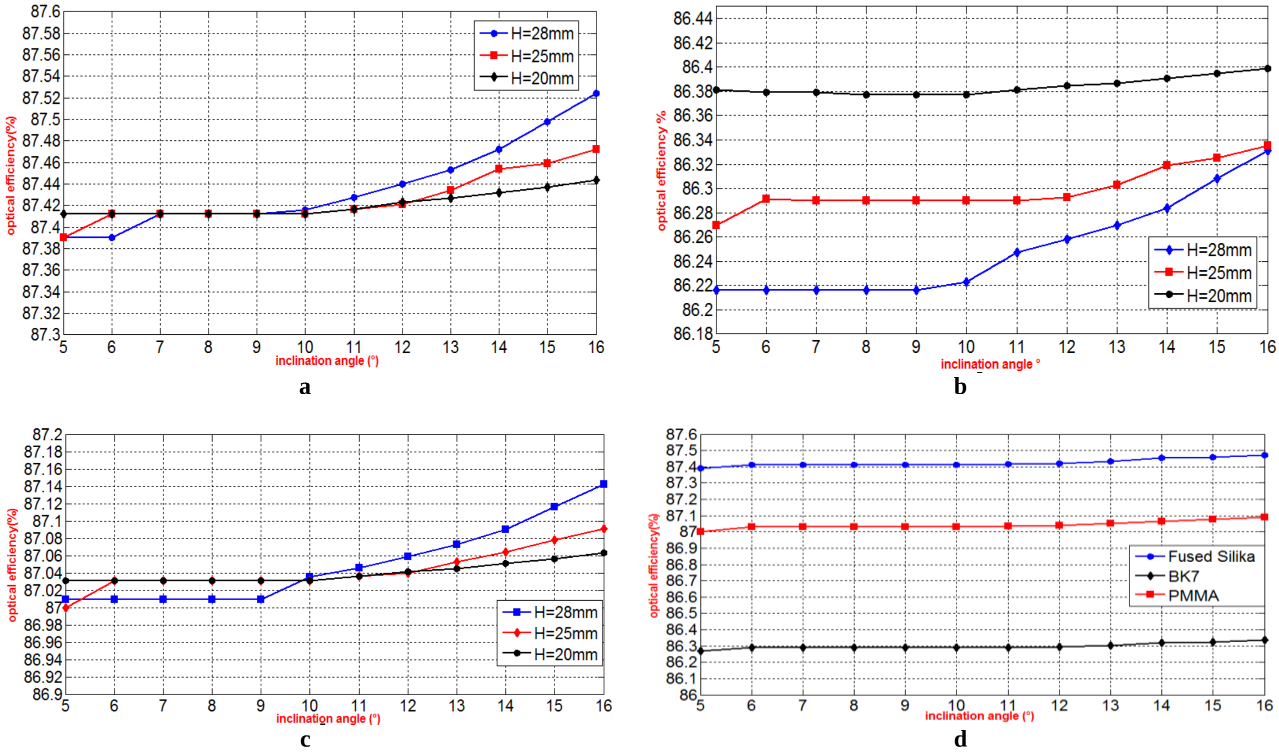

Figure 4. optical efficiency versus inclination angle:
(a): Fused Silika, (b): BK7, (c): PMMA, (d)H=25mm

Figure 4 revealed that the optimum value of inclination angle α was 16° to achieve a highest optical efficiency for the three values of H. Moreover when H is fixed to 28mm the optical efficiencies were maximal for Fused Silika (87,524%), and PMMA (87,124), while it is at maximum for BK7 at H=20mm (86,4%).

3.4. Optical tolerance and irradiance distribution

Figure 5 shows and compares the optical efficiencies of the three values of H (20mm, 25mm and 28mm) of the inverted truncated pyramid for the fused silica under different incidence angles. It can be observed that the pyramid with height equal to 28mm is sensitive to the deviation of the incidence angle.

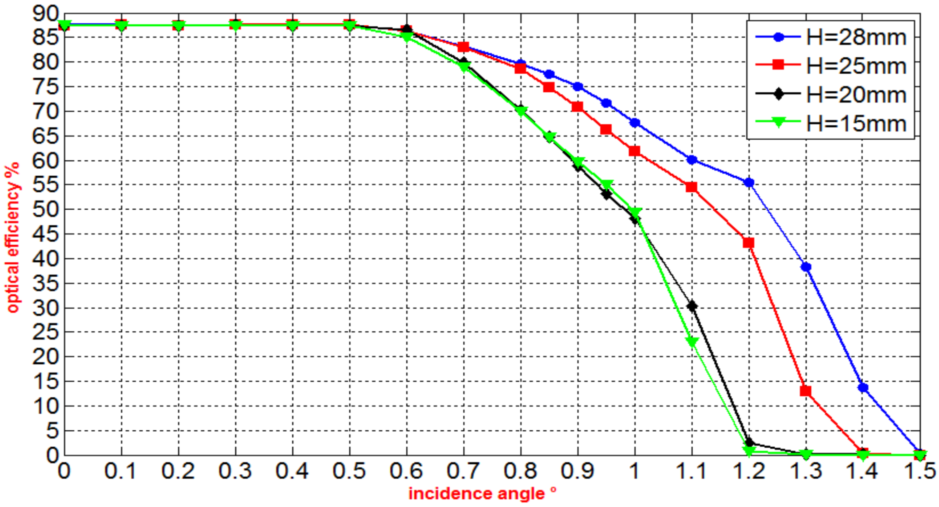

Figure 5. Optical efficiency versus incidence angle

Table 2. Comparison of the optical performance of the Fresnel lens with pyramids

Height (mm)	28	25	20	15
$\theta_{90\%}$	0,82	0,81	0,72	0,71
$\theta_{80\%}$	0,96	0,91	0,82	0,8
Optical efficiency under normal incidence (%)	87,524	87,472	87,444	87,462
Optical efficiency at $\theta_{90\%}$(%)	78,771	78,724	78,699	78,715
Optical efficiency at $\theta_{80\%}$ (%)	70,019	69,977	69,955	69,97

Table 2 summarize the optical characteristics and comparison of CPV unit with pyramids with various heights as shown pyramid with H=28mm exhibits a better acceptance angle $\theta_{90\%}$=0,82° and $\theta_{80\%}$=0,96°($\theta_{90\%}$and$\theta_{80\%}$are the incidence angle corresponding respectively to 90% and 80% of the maximum optical efficiency at normal incidence)than other pyramids and the corresponding optical efficiency at the acceptance angles are respectively 78,77% and 70,02%.

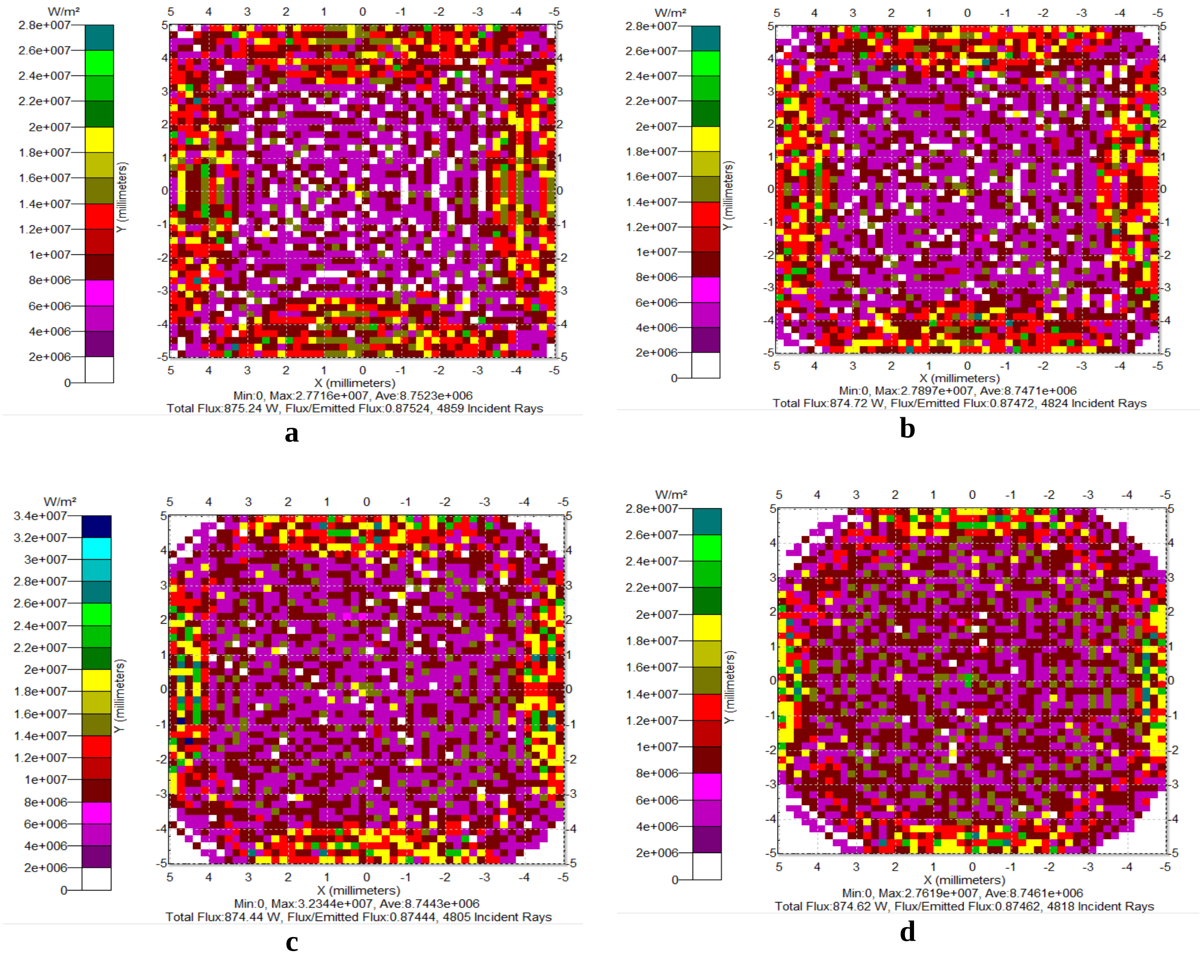

Figure 6. Maps of output flux at the exit of the pyramid:
(a) H=28mm, (b) H=25mm, (c) H=20mm, (d)H=15mm

Figure 6 displays the irradiance distribution under normal incidence for different values of H. It can be seen that all pyramids give uniform irradiance distribution over cell and that pyramid with H=28mm gives the best homogeneity.

4. Conclusion

This study presents a design of an inverted truncated pyramid to improve the performance of CPV module. Inclination angle and height are optimized to achieve high values of optical efficiency and acceptance angles. Different sizes of pyramids were evaluated by ray-tracing simulation. We found that when concentrator height and inclination angle are set to be 28mm and 16° respectively and the used material is fused silica, we achieve a highest optical efficiency 87,524% as well as a good acceptance angle $\theta_{80\%}$=0,96°

Acknowledgments

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