Optical modeling and Performance Design Of A Fresnel Lens For CPV Units

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Abstract. In CPV technology, a focus on keeping low costs has led most recent designs to use concentration ratios of 1000X or higher. For that, many high-concentration photovoltaic systems use refractive Fresnel lenses because it is one of the main transmission-type concentrators. In this work, a solar concentrator system composed from a typical Fresnel lens made of PMMA, with an effective diameter of 350mm and a squared solar cell of 10x10mm is proposed. The design of a Fresnel lens is introduced; we studied and analysed a squared design configurations with multiple tuning of focal lengths, facet spacing and an extended range of wavelengths. The results show that the Fresnel lens is performant in the visible spectrum with facet spacing of 1mm and the focal length between 265 to 350mm. The acceptance angle of the whole system was between 0.6 to 0.8° and the optical efficiency obtained by simulations was between 80 to 90%.

1. Introduction

CPV technology is becoming a trend to create a cost-effective system with a high level of concentration compared to other photovoltaic technologies, [1][2]. This technology increases the efficiency of cell conversion and reduces cell size, which also reduces the contribution of photovoltaic costs to the entire system [3][4]. The CPV system is based on the use of optical elements that can be refractive (Fresnel lenses), reflective (Mirror), or both.

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Each CPV system is characterized by its concentration ratio which given by:

$$C = C_{geo} \times \eta$$

(1)

Where $C_{geo}$ denotes the geometrical concentration and $\eta$ the optical efficiency. Those parameters are respectively given by:
\[ C_{geo} = \frac{A_{in}}{A_{out}} \]  \\
\[ \eta = \frac{P_{in}}{P_{out}} \]

Where \( A_{in} \) and \( A_{out} \) are the input and the output aperture of CPV system as indicated at fig.1

Figure 1. Schematic view of a solar concentrator

The Fresnel lens [5][6] has been widely used as a concentrator in the CPV. It is considered as one of the main transmission-type concentrators which has several advantages on engineering such as lighter weight, larger allowable error of track and easier to receive light etc…[7]. Moreover this optical element has two disadvantages. The first, the optical concentrator, has a long focal length that increases the volume and weight of the system. The second, the distribution of the irradiance on the solar cell, is non-uniform and creates a hot spot, which decreases the efficiency of the conversion and decreases the reliability, the lifetime of the photovoltaic system [8]. Tver'yanovich et al. [8] has early studied how profile effected of the performance of solar-engineer Fresnel lens. Khalil et al. [9] designed a linear focusing flat Fresnel lens and found that the edge-prism has bad transmittance. Leutz et al. [10] designed a convex-shaped Fresnel lens by using edge ray principle. This Fresnel lens has a short focal length and high concentration ratio. The tested optical efficiency reaches to 72%. Xinglong et al. [11] analysed the relation between transmittance and incident angle quantitatively, which were based on Fresnel lens and the reversibility of light.

In this work, we propose a solar concentrator system composed from a typical Fresnel lens made of PMMA, with an effective diameter of 350mm and a squared solar cell with 10x10mm. The design of a Fresnel lens is introduced; we studied and analysed a squared design configurations including several focal lengths, facet spacing and an extended range of wavelengths.

The rest of the paper is organized as follows: section 2 introduces the design and theoretical background of Fresnel lens; section 3 is dedicated to analyse serval studies and cases of Fresnel lenses.

2. Design of Fresnel lens
The CPV optics constitute a typical design problem that contains both the bundle coupling problem for obtaining maximum acceptance-concentration product and the prescribed irradiance to get uniform irradiance distribution on the solar cell area [12]. The design method includes the inner saw teeth of Fresnel lens that work by total internal reflection and refraction. The Fresnel lens is composed of several prisms as shown in Fig.2,a. A typical Fresnel lens with grooves facing inwards will be presented here. The design has an analytical solution and follows Tver'yanovich [8]. In accordance with Fig. 2, several parameters can be set up to describe the prism which are: $\theta_a$ is an angle between the normal of the receiver and the refractive ray, $\alpha_p$ is an angle between the normal of the Fresnel lens's facet and the incident ray, $\beta_p$ is an angle between the normal direction of the Fresnel lens's facet and the refractive ray, $f$ is the focal length and $d$ is the Fresnel lens diameter as illustrated in Fig.2,b.

\[
\begin{align*}
n \sin \alpha_p &= \sin \beta_p \quad (4) \\
\sin \theta &= \frac{d}{2f} \quad (5) \\
\beta_p &= \theta + \alpha_p \quad (6) \\
F_\# &= \frac{f}{d} \quad (7)
\end{align*}
\]

Using the above equation, we have designed a square Fresnel lens with 350mm as diameter and 265mm as focal length as sketched in Fig.3. The material used in this design is polymethyl methacrylate (PMMA), which is a typical optical plastic with a refractive index of 1.49.
3. Simulation Results

3.1. Effect of facet spacing on Fresnel lens Performance

In order to evaluate our design. The optical performance are analysed by using the software, TRACEPRO. Firstly, we will discuss the influence of the facet spacing on the intensity distribution, optical efficiency and the acceptance angle. For this test, the solar spectrum is the visible range and the focal length is fixed to 265mm. Figures 4 and 5 show the evolution of the intensity and the optical efficiency according to facet spacing.

The intensity decreases from 1.2 $10^8$ W/m$^2$ to 9.5 $10^7$. It should be noted that this figure illustrates the central intensity of the receiver. Concerning the optical efficiency, it increases slightly for facet spacing less than 1 mm and begins to decrease with increasing the facet spacing. In fact, for a fixed diameter lens, and by increasing the facet spacing (the number of prism decreases), the angle of the prism will be increased, and consequently, the size of the prism will be larger, this will produce losses resulting from the total internal reflection and geometrical losses (the losses that occur due to the divergence of the optical beam) for the rays that coincide with the ends of the prisms.
Figure 4. Intensity in function of facet spacing

Figure 5. Optical Efficiency in function of facet spacing

Table 1. Acceptance angle Vs facet spacing.

| Facet Spacing (mm) | 0.2 | 0.4 | 0.6 | 0.8 | 1   | 2   | 3   | 4   |
|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Acceptance Angle (°) | 0.6 | 0.7 | 0.7 | 0.8 | 0.7 | 0.6 | 0.6 | 0.6 |
3.2. Effect of focal length on Fresnel lens Performance

In this part, we have varied the focal length of our Fresnel lens from 175 to 700mm and evaluate its optical performances. At this moment, the solar spectrum used is extended from 300 to 700nm (Visible spectrum) and the facet spacing is fixed to 1mm.

Fig.6 shows the simulation of our design. We can observe that for the short focal length some of light are reflected by TIR and don’t reach the receiver, however, for the long focal length, all rays reach the receiver.

Fig.7 illustrates the evolution of intensity distribution on the receiver for several focal lengths. The intensity start to increase reaches a maximum from 265 mm to 350 mm (f-number from 0.75 to 1) as focal length, and decrease with increasing focal length in the case of intensity, but the observed peak becomes larger indicating some homogenization of the intensity repartition on the receiver. In fact, one can easily notice the high and narrow peak for the focal lengths between 175 and 350mm.

Fig.8 shows the optical efficiency versus the focal length. The optical efficiency start to increase also reach a maximum in the focal range 265 mm to 350 mm (f-number from 0.75 to 1) as focal length, and start to decrease, beyond these values, but more slowly.

Table1 resumes the acceptance angle of the whole concentrator system. We observe that the acceptance angle is stable from 175mm to 350mm and starts to decrease with the larger focal lengths.

Finally, we can say that the focal length cannot be short because some of light are reflected by TIR causing an unbearable optical efficiency as shown in fig.6 and fig.8. For the long focal lengths, they would result in a too deep, thus expensive module.

Figure 6. Simulation of Fresnel lens
Figure 7. Flux intensity on the receiver for several focal length

Figure 8. Optical Efficiency versus focal length

Table 2. Acceptance angle Vs focal length

| Focal length (mm) | 175 | 265 | 350 | 525 | 700 | 175 | 265 | 350 |
|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Acceptance Angle (°) | 0.7 | 0.8 | 0.8 | 0.7 | 0.6 | 0.6 | 0.6 | 0.6 |

3.3. Effect of wavelength on Fresnel lens Performance

For the current study, we set the focal length to 265mm, facet spacing to 1mm and we vary the wavelength from 0.1 to 1.4μm. We obtained the evolution of intensity and the optical efficiency according to the wavelength variation. As fig.9 and Fig.10 show the effect of wavelength variation on
intensity and optical efficiency. It is noted that the intensity and the optical efficiency are high in the ultra violet and the visible and decrease with the increase of the wavelength. These results are due for two reasons; the first is the transmission of the PMMA material as a function of the wavelength. PMMA transmission is higher in the UV and visible (92 %), however, it is low in the infra-red, the second reason is the evolution of the irradiance depending on the length of wave, since, one finds a strong irradiance in the UV and the visible one and weak for the infrared. The acceptance angle in this case is still stable whatever the wavelength as sketched in table 3.

![Flux intensity in function of wavelength](image1.png)

**Figure 9.** Flux intensity in function of wavelength

![Optical Efficiency in function of wavelength](image2.png)

**Figure 10.** Optical Efficiency in function of wavelength

| Table 3. Acceptance angle Vs focal length |
|------------------------------------------|
| wavelength (μm) | 0.2 | 0.6 | 1 | 1.4 | 0.2 | 0.6 | 1 | 1.4 | ALL |
|-----------------|-----|-----|---|-----|-----|-----|---|-----|-----|
| Position on the receiver (mm)            |     |     |   |     |     |     |   |     |     |
In order to valid and to generalize the study results. An additional test configuration is performed. The test concerned the diameter of the lens. We have varied the diameter of Fresnel lens from 50 mm to 400mm.

We found at each time that the optical efficiency is high when the f-number was at 0.75 and at 1. We found also that it high at the visible spectrum

4. Conclusion

We have presented in this paper a performance design of Fresnel lens and detailed configurations studies with multiple tuning of focal lengths, facet spacing and an extended range of wavelengths. Results show that the intensity and the optical efficiency start to increase reaching a maximum from 265 mm to 350 mm (f-number from 0.75 to 1) as focal length, and decrease with increasing focal length in the case of intensity, but the optical efficiency is still stable. We observed that the focal length could not be shorter because some of light are reflected by TIR causing an unbearable optical efficiency. For the long focal lengths, they would result in a too deep, thus expensive module. Concerning the acceptance angle of the whole concentrator system. We observe that the acceptance angle is stable from 175mm to 350mm and starts to decrease with the increment of the focal length.

We have also seen that the intensity and the optical efficiency is higher in the case of the ultra violet and it decreases with the increment of the wavelength. The acceptance angle in this case is still stable whatever the wavelength. Concerning the facet spacing, the intensity distribution and the optical efficiency increase with the increment of facet spacing. Concerning the CI_C77ance angle, we observed that is stable and higher from 0.6mm to =1mm. From this study, we can say that the Fresnel lens is performant in the visible spectrum with facet spacing of 1mm and the focal length between 265 to 350mm. The acceptance angle of the whole system was between 0.6 to 0.8° and the optical efficiency was between 80 to 90%.

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