Comparative study of two CPV optical concentrators, using a Fresnel lens as primary optical element

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Abstract. In this work, the performances of two optimized reflective secondary optics elements a CPC (Compound Parabolic Concentrator) and a Cone for use in a CPV concentrator system are studied using ray-tracing simulation for the same primary optical element: a Fresnel lens. These optical elements are compared in terms of concentration, acceptance angle, exit angle and output light distribution. Our results show that the power distribution at the end of the concentrator is more uniform in the case of the cone. The optical efficiency is higher when the secondary element is placed at a distance \( f + R \tan \theta \) with \( f \) the focal length, \( R \) the input radius of the secondary optical element and \( \theta \) the acceptance angle of the secondary optical element. Also, we found that the length and the input radius of each optical element decrease when the Fresnel lens diameter increases but the input radius of the CPC stills the larger. Finally, our calculation show that the CPC is longer than the cone while the Fresnel lens diameter is less than 200 mm and beyond this value both the cone and the CPC mostly present the same length.

1. Introduction
The main idea that motivates a CPV system is the cost reduction by using optical elements to focus light on solar cells thus reducing the used surface of expensive solar cells materials. The optical concentrators generally use a primary and a secondary element to respectively focus and homogenize the light on the receiver.
In this work, a compound parabolic concentrator (CPC) and a cone are used as secondary optical concentrator elements for CPV and are associated with a Fresnel lens as a primary stage. The achievements concern the performances comparisons in term of concentration, acceptance angle, output light distribution and the exit angle.
A part of this work concerns the sizing of each element starting from a targeted geometrical concentration ratio of 2000x. For the cone design, the number of inside reflections is also considered as a parameter.
Finally, the optimal position of the considered optical secondary concentrators facing the Fresnel lens is studied.
2. Optical elements
The Fresnel lens is characterized by its f_number, FN/# defined by [1]

\[
FN/# = \frac{f}{d}
\]  (1)

\[
\tan \theta = \frac{d}{2f}
\]  (2)

Where f, d and \(\theta\) are, respectively, the focal length, the diameter and the incidence angle of the Fresnel lens.

![Figure 1. Illustration of the f_number for the Fresnel lens](image)

A CPC is defined by its geometrical parameters (see fig.2): the exit and the entrance radiuses \(r_{cpc}\) and \(R_{cpc}\) respectively, the incidence angle, \(\theta\), the length \(L\), and the focal length \(F_{cpc}\). All these parameters are dependent and related by the following equations: [2]

\[
R_{cpc} = \frac{r_{cpc}}{\sin \theta}
\]  (3)

\[
F_{cpc} = r_{cpc}(1 + \sin \theta)
\]  (4)

\[
L_{cpc} = \frac{R_{cpc} + r_{cpc}}{\tan \theta}
\]  (5)

![Figure 2. Geometrical parameters of the Compound Parabolic Concentrator (CPC)](image)
The cone is defined by its output and input radiuses $r_{cone}$, $R_{cone}$, the output and input angles $\theta_{i}$, $\theta$, the angle of the cone $\alpha$, its length $L_{cone}$ and $a_{n}$ is difference between the input and the output radius of the cone, [3]. The length of the cone depends on the inside number of ray reflections, $n$. All these parameters are given by the following equations [3, 4]:

\[ \theta_{f} = \theta + 2n\alpha \] (6)

\[ R_{cone} = r_{cone} + \sum_{n=1}^{n_{max}} a_{n} \] (7)

\[ L_{cone} = \frac{\sum_{n=1}^{n_{max}} a_{n}}{\tan \alpha} = \frac{R_{cone} - r_{cone}}{\tan \alpha} \] (8)

**Figure 3.** Geometrical parameters of the Conical Concentrator

### 3. RESULTS AND DISCUSSION

#### 3.1. Influence of the Fresnel lens diameter on the sizes of the secondary elements

For the first comparison, we varied the Fresnel lens diameter from 50 mm to 500 mm to figure out its influence on the size, using the above equations (3-8). The number of reflections was firstly fixed to 4 ($n=4$).

As shown on fig. 4 and fig. 5, both the length and the input radius of each optical element decrease when the Fresnel lens diameter increases but the input radius of the CPC is the larger. Concerning the length, we can notice that the CPC is longer than the cone as long as the Fresnel lens diameter is less than 200 mm otherwise the two lengths are approximately equal. It is important to note that we choose number of reflections to 4 because this number allows to a cone size almost near the size of the CPC.
3.2. Design considerations

As a design example, we target a geometrical concentration ratio of 2000×. The exit radius of the two secondary optical elements is fixed to 5 mm, which is the classical size for commercial solar cells for CPV. The Fresnel lens diameter, calculated using the geometrical concentration ratio, is 223.6 mm and the acceptance angle of the two elements is fixed to 31.7°. Considering these parameters, we obtain for our secondary optical elements the sizes reported in table 1.
Finally, we studied optical efficiencies versus the distance of the secondary optical element from the Fresnel lens. The optical axe is set as a z-axis whose origin $z = 0$ coincides with the position of the Fresnel lens.

Three possible positions of the secondary optical element are a priori possible without any optical losses. The first one, $z$, is defined by the focal length of the lens (fig. 6,a), the second and the third positions $z_{\text{max}}$ and $z_{\text{min}}$ are respectively defined by the place where the incoming rays size fits with the input diameter of each element after and before the focal position of the lens (fig. 6, b and fig 6, c).

These positions are given by:

$$z_{\text{max}} = f + \frac{R}{\tan \theta} \quad (9)$$
$$z_{\text{min}} = f - \frac{R}{\tan \theta} \quad (10)$$

### Table 1. Size of secondary optical elements (R, r and L) for the considered design example

|       | R (mm) | r (mm) | L (mm) |
|-------|--------|--------|--------|
| Cone  | 3.9469 | 2.5    | 11.3142|
| CPC   | 4.7656 | 2.5    | 11.7912|

![Diagram](image)
Figure 6. z-positions of the secondary optical element (a) $z=f$ (secondary optical element at the focal length of Fresnel lens) (b) $z=z_{\text{max}}$ (c) $z=z_{\text{min}}$

Fig 7 shows the power distribution of the output of the cone and the CPC for an incidence angle of $0^\circ$. We notice that for the three positions, the highest density focuses in the center of the seconcadries exit, and it decreases in the extremity. At $z=f$, the cone presents a homogeneity better than the CPC. At $z=z_{\text{max}}$ presents the high density ($6.5 \times 10^8$ W/m$^2$ for CPC and $5.5 \times 10^8$ W/m$^2$ for the cone) and the CPC has the worst homogeneity.

Table 2 resumes the values of the optical efficiency for the two concentrators with an incidence angle of $0^\circ$. 
Table 2. The optical efficiency of secondary optical elements at 0°.

|              | z=f | z=z_{max} | z=z_{min} |
|--------------|-----|-----------|-----------|
| Cone         | 84.62% | 85.64% | 51.06% |
| CPC          | 85.033% | 85.65% | 49.59% |

We note that the optical efficiency is higher when the secondary is in the position of z=z_{max}.

To calculate the optical concentration C, we use the following equation [5]:

\[ C = C_{opt} \times C_{geo} \] (11)

Where \( C_{geo} = \frac{\text{input aperture}}{\text{output aperture}} \) is the geometrical concentration ratio and \( C_{opt} = \frac{\text{input rays}}{\text{output rays}} \).

From optical simulation and using the concentration equation (11), we calculate achieved concentrations ratios with several incidences angle from 0 to 2°. Results are presented on fig 8 and show that the concentration decreases with the increment of incidence angle when the concentrator is placed at z or z_{max} with a more pronounced decrease for the two studied elements. In this case, the concentration ratio at 0° is about 1700x. When the concentrator is placed at z_{min}, the concentration ratio increases to a maximum around 0.4° and then decreases. In this position (z= z_{min}) the achieved concentration ratio stills around 1000x indicating that this position is not optically efficient.
(a)
4. Conclusion

In this work, we have presented a comparison of performances of two CPV optical concentrators, using a Fresnel lens as primary optical element. These elements are the CPC and the cone. Our results show that the length and the input radius of each optical element decrease when the Fresnel lens diameter increases but the input radius of the CPC is the larger. Concerning the length, we obtained that the CPC is longer than the cone as long as the Fresnel lens diameter is less than 200 mm.
Otherwise; the two lengths are approximately equal. Regarding concentration, and after studying the best placement of the secondary element, we noticed that it is enhanced in the case when the secondary optical element is a cone but when the angle of incidence increases, the concentration is higher in the case of the CPC placed at $z_{\text{max}}$.

**Acknowledgments**

This work is supported by the Research Institute for Solar Energy and Renewable Energies (IRESEN) in the framework of the LOuCOuM project.

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