Parametric Optimization and Performances Analysis Of Four Secondary Optical Elements For Concentrator Photovoltaic Systems

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Abstract- The study concerns a general, parametric and performances analysis of four secondary optical elements (SOE) to use for Concentrator Photovoltaic Systems (CPV) using the same primary optic element: the Fresnel lens (FL). It concerns the Compound Parabolic Concentrator (CPC), the Crossed Compound Parabolic Concentrator (CCPC), the Cone and Pyramid. The study starts from optical modeling and considers several classical materials, with various refractive indexes in order to get a clear idea about their influences on the efficiencies, the sizes and the geometrical needs of the SOEs. The performances of the whole concentrator systems are compared in term of achieved effective concentrations, acceptance angles, output light power distribution and tolerances in the placement of the secondary element regarding the FL. Based on the étendue law, the geometrical considerations reveal that the length and the input aperture size of the whole SOEs increase with the increase of the refractive index of the considered material. Results show that the pyramid-based concentrator gives the more uniform irradiance distribution and the high optical efficiency whatever the used material, and the largest tolerance angle never reported. At the end, to easiest the comparison of the four elements, a merit graph is developed and proposed.

Keywords Primary optical element; Secondary optical element; CPV; Fresnel lens; Optical Efficiency; Acceptance angle, CPC, CCPC, Pyramid, Cone

Table 1. Nomenclature

a_N	Half of the difference between the width of the exit and width of the entrance	n_1	Index of the entrance medium
A_{in}	Entrance aperture area	n_2	Index of the exit medium
A_{out}	Exit or receiver area	n_s	Index of the secondary optical element
C	Whole Concentration ratio	N	Number of reflection inside the cone and the pyramid
C_{geo}	Geometric concentration ratio	P_{in}	Power at the entrance of the system
C_{opt}	Optical concentration ratio	P_{out}	Power at the exit of the system
CPC	Compound Parabolic Concentrator	PMMA	Poly Methyl MethAcrylate
CCPC	Crossed Compound Parabolic Concentrator	POE	Primary Optical Element
CPV	Concentrated Photovoltaic	r	Exit radius of the SOEs
D	Fresnel lens diameter	R_{cone}	Entrance radius of the cone
f	Focal length of Fresnel lens	R_{cpc}	Entrance radius of the CPC
FL	Fresnel Lens	TEC	Thermal expansion coefficient
F_{cpc}	Focal of the parabolic side of the CPC	SOE	Secondary Optical Element

HCPV	High Concentrated Photovoltaic	θ	Entrance angle of the SOEs
L_{cone}	Length of the Cone	θ_{in}	Solar angle
L_{cpc}	Length of the CPC	θ_{out}	Exit angle
A_{out}	Exit or receiver area	α_{cone}	Angle of the Cone

1. Introduction

The unit surface energy of the incoming solar radiation is the low intensity and this has led to the idea of using concentrator systems [1]. Concentrated PhotoVoltaic is one of the promising solutions for clean electricity generation from solar energy. It represents a high efficiency alternative to the traditional flat plate module [2]. This technology allows a significant reduction of the required cell area, to produce a given amount of electricity power. These systems however use only direct solar radiations and needs continuous and efficient solar tracking systems. A carefully concentrator photovoltaic system design is then required in order to increase cells efficiencies by collecting a high solar radiation amount and focusing it on the small cell surfaces. A solar concentrator design must necessarily pass through a simulation stage to estimate its efficiency and its various performances (acceptance angle, flux distribution, etc...). A multitude of concentrating solar energy systems is proposed in the literature and most of them are generally composed of two elements: a Fresnel lens or V-trough mirror [3] as a primary optical element (POE) and a secondary element (SOE). The Fresnel lenses are usually manufactured from PMMA (Poly Methyl MethAcrylate) or Glass. The PMMA seems to be a best choice with good transmission, low cost, excellent uniformity [4-6] and not easily breakable. Two roles are assigned to the SOE, the first is to ensure as most as possible a homogenous distribution of the collected sunlight, from the side of the POE, onto the solar cell and the second is to reduce sensitivity to solar tracking error [7,8]. The geometrical parameters of the SOEs are intimately dependent on both the design and shape of the POE, the size of the solar receiver [9] and on the used material for their manufacturing. For the SOEs, the Compound Parabolic Concentrator (CPC) seems to be one of the most studied and is considered as a rather good concentrator working with the largest acceptance angle [10-12]. Theoretically, the CPC is able to maximize the concentration as much as theory predicts but one of its major disadvantages is that it provides a deep non-uniform irradiation distribution over the cell. Moreover, it is usually manufactured from glass, which is less expensive for CPV applications, since it requires large amounts of material, and the optical surfaces usually need to be polished after manufacturing [13]. The exit shape of the CPC is circular however; the commercially available CPV cells are a squared or rectangular shape, that's why several works [14, 15] introduced the Crossed Compound Parabolic Concentrator (CCPC) to match this shape of receivers. Baig et al. [14] and Sellami et al. [15] analyzed a dielectric CCPC designed to have a geometric concentration of 3.6x, made from clear polyurethane material for low concentrating photovoltaic system. They reported a maximum optical efficiency of 73.4% but the light distribution was non-uniform.

Other shapes of the SOEs have been studied; Kiatgamolchai and Chamni [16] studied and formulated the theory of a two-dimensional cone concentrator where a high reflectivity value for all the useful wavelengths must be insured in order to maintain a good optical efficiency. After that, another SOE inspired from the cone, the pyramid, with a rather rectangular shape was proposed to homogenize the irradiance distribution over the cell [11] and can be easily manufactured and coupled to a primary lens.

Victoria et al. [11] reported on the performances of solar concentrators using a primary aspheric lens and a CPC, a pyramid and a cone as a SOE. Comparison was performed in terms of optical system efficiency, acceptance angle and irradiance distribution over the cell. They reported that the CPC shows the better acceptance angle, ±1,4° for 90% of relative transmission and that the cone and the pyramid show the best optical efficiency with a best irradiance distribution for the pyramid. Nevertheless these studies has always considered a fixed material and no systematic and parametric study has been performed for instance to compare performances of SOEs manufactured from several materials with several refractive indexes to investigate their effects on both the sizes and efficiencies of CPV concentrators.

In this work, our aim is to produce a general, parametric and comparative study of four photovoltaic concentrators, dedicated to high concentrating systems, formed by a same FL as a primary element and several geometrical shapes to be used in CPV systems: CPC, CCPC, Pyramid and cone. For the Fresnel lens, several configurations and design variants are considered and tested mainly depending on the different focal length, facet spacing and lens thickness. For the manufacturing of the secondary element, several candidate materials with refractive indexes ranging between 1.4 - 1.7 are considered. Besides the optimal placement of each SOE regarding the FL is determined to find the best placement.

Note that the final purpose of this study is to design a solar concentrator in the framework of a research and development project named LOUCOUM PROJECT in Morocco concerning the design of a low cost CPV Panel.

The rest of the paper is organized as follows: section 2 introduces the theoretical background; section 3 is dedicated to the secondary element design. Results and discussion are presented in section 4 and section 5 highlights the major r results in a conclusion. The used characters in equations and in the text are all defined in table 1

2. Theoretical Background

Figure 1 shows a typical view of the considered system. The whole concentration ratio is given:

$$C = \eta \times C_{geo} \tag{1}$$

Where C_{geo} denotes the geometrical concentration and $\boldsymbol{\eta}$ the optical efficiency. Those parameters are respectively given by:

$$C_{geo} = \frac{A_{in}}{A_{out}} \tag{2}$$

$$\eta = \frac{P_{out}}{P_{in}} \tag{3}$$

Using the étendue law [17], Eq. (2) can be rewritten for two separate medium with refractive indexes n_1 and n_2:

$$C_{geo} = \frac{A_{in}}{A_{out}} = \left(\frac{n_2 \sin\theta_{out}}{n_1 \sin\theta_{in}}\right)^2 \tag{4}$$

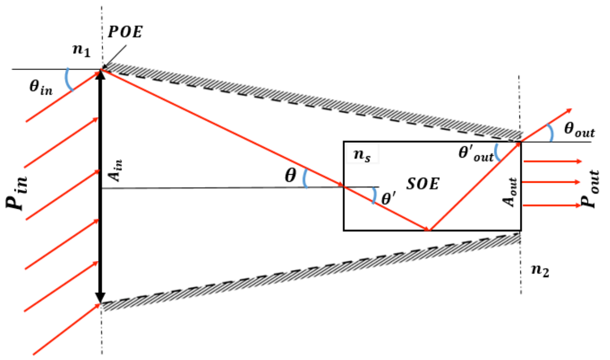


Fig. 1. Schematic view of a two stage solar concentrator. The dashed lines correspond to external borders of the system

The Fresnel lens is characterized by its f number, F/#, defined by:

$$F_{/\#} = \frac{f}{D} \tag{5}$$

and its opening angle 2θ given by:

$$\tan\theta = \frac{D}{2f} \tag{6}$$

From the refraction law, the outside and inside angles of the optical system are related by the following equation (see figure (1)) [17]:

$$\sin\theta = n_s \times \sin\theta' \tag{7}$$

$$\sin\theta_{out} = n_s \times \sin\theta'_{out} \tag{8}$$

3. Design of the Secondary Optical Elements

3.1. CPC shape

A 2D section view of a CPC shape concentrator is shown in Fig. (2). The CPC is defined by the following parameters and mainly dependent to its entrance limit angle θ and exit angle θ'_{out} given by eq. 9-11.

$$R_{cpc} = \frac{r}{\sin\theta'} \tag{9}$$

$$F_{cpc} = r\left(\sin\theta'_{out} + \sin\theta'\right) \tag{10}$$

$$L_{cpc} = \left(R_{cpc} + r\right)\cot\theta' \tag{11}$$

The entrance limit angle is chosen equal to the opening angle of the Fresnel lens, given by Eq. (5).

The CCPC is described by the same set of equation with squared entrance, exit and edges.

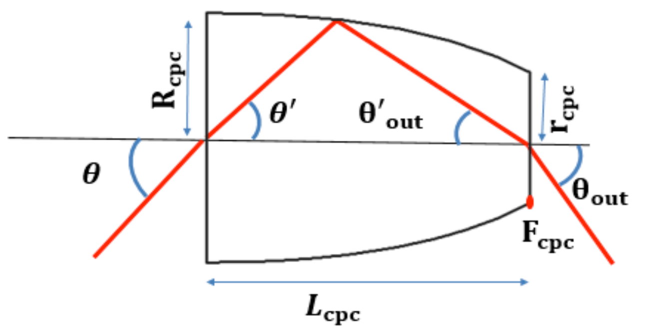


Fig. 2. 2D Sectional view of a Compound Parabolic Concentrator.

3.2. Conic shape

The design parameters of a cone, shown in Fig.(3), depend on the number of the reflections, N, that an incoming ray undergoes inside the cone before exiting it. Its design parameters are the length L_{cone}, the output and input radius r_{cone} , R_{cone}. a_N (see Fig.(3)) is the difference between the width of the exit and the entrance radius. The angle of the cone α_{cone} is derived from these parameters and highly influences the propagated ray direction. In fact for only one reflection, the light ray is deviated with $2\alpha_{cone}$ as can easily verified by geometrical considerations [11].

Hence, a cone can be considered as a series assembly of several small cones, the length of each one is limited by the impact of two successive reflections, of a given light ray, on the cone surfaces. The entrance surface for an intermediate cone is equal to the exit surface of its predecessor. Then the exit angle, θ'_{out} is given by:

$$\theta'_{out} = \theta' + 2N\alpha_{cone} \tag{12}$$

The entrance radius (see Fig. (3)) is given by:

$$R_{cone} = r + \sum_{N=1}^{N_{max}} a_N \tag{13}$$

and the cone length is:

$$L_{cone} = \frac{R_{cone} - r}{\tan \alpha_{cone}} \qquad (14)$$

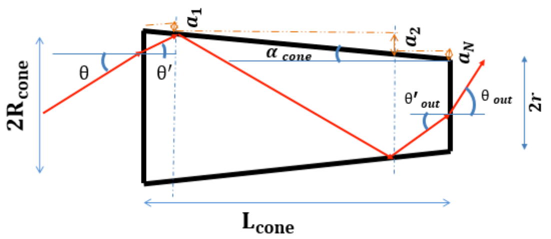


Fig. 3. Sectional view of Conical Concentrator.

The pyramid, the last considered SOE, is inspired from the cone and therefore described by the same set of equations [18].

3.3. Materials properties

Typical spectral response of the mostly available multi-junction solar cells in the market, and used in CPV systems, is shown on figure (4) [19]. The quantum efficiency is higher in the wavelength range 400-1500nm, then the used materials for the solar concentrator manufacturing must have a high transmission coefficient in this wavelength interval. A list of candidate material, easily available in the market, and corresponding to this high transmission requirement is presented in table 2. Their refractive indexes vary in the 1.4-1.7 interval and their transmission coefficients are ranging between 29% and 100%, respectively, for these wavelength range. The targeted concentrator is composed from a typical circular Fresnel lens made of PMMA and having the parameters listed in table 3, and a SOE with a squared or circular output fitting with a receiver of 10mm × 10mm.The whole concentrating system length must not exceed 390mm. Our system is considered as exposed to solar rays with an incident angle of 0.28°, and exit angle reaching 10° obtained from the Eq. (1).

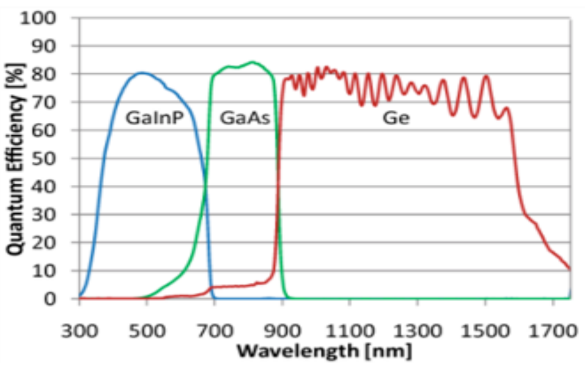


Fig. 4. Typical spectral response of the multi-junction solar cells.

Table 2. Materials used to build the SOE.

Material	Refractive Index	Transmission	Wavelength range
PDMS	1.39	88%	(200 - 1050nm)
Fused Silica	1.46	100%	(210 - 3710nm)
FK1	1.473	29%-95.6%	(300 - 2500nm)
PMMA	1.49	92%	(200-2100nm)
Soda Lime glass	1.5	5% 50% 90%	(300nm) (350nm) (380-680nm)
BK7	1.51	99%	(300 - 2500nm)
B270	1.52	92%	(350 - 2500nm)
Baf10	1.67	99.6%	(350 - 2500nm)

Table 3. Parameters of the used Fresnel Lens.

Parameters	Value
Diameter (mm)	350
F/#	0.75
Focal Length (mm)	265
Facet spacing (mm)	1
Thickness (mm)	0.5
Opening angle (°)	33.44

4. Results and Discussion

4.1. Geometrical considerations of the four SOEs

The main goal is to design and compare performances of four concentration systems having the same input aperture (the Fresnel lens diameter), the same length and two output aperture forms, squared with a side of 10mm or circular with a diameter of 10mm.

We first calculated the length and the input radius variation, versus the refractive index, of each SOE by using equations (7-14). Fig. (5) shows the length of the CPC, CCPC and those of the pyramid and cone for five numbers of reflections. We notice that the length of each element increases with the refractive index. For the design of the system, we consider the length of the CPC and CCPC as a reference as they are imposed by the opening angle of the FL, then we vary the number of reflection N inside the Cone and the pyramid to get the same size. For instance, for the three number of reflection N=2.2, N=2.3 and N=2.4, the cone and the pyramid can have the same length as the CPC and the CCPC, but with a different refractive indexes in each case.

Fig. (6) shows that the input radius, for each element, increases with the refractive index but with a high slope for the CPC-shaped form.

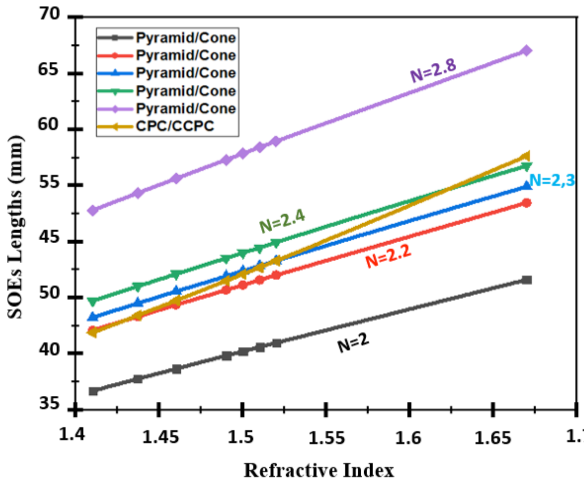


Fig. 5. Length of the secondary optical elements versus the refractive index

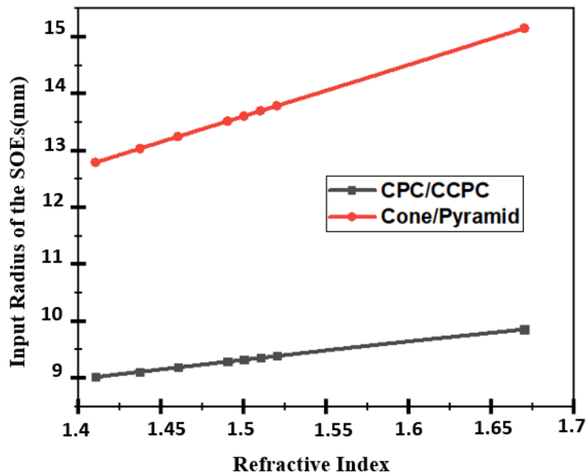
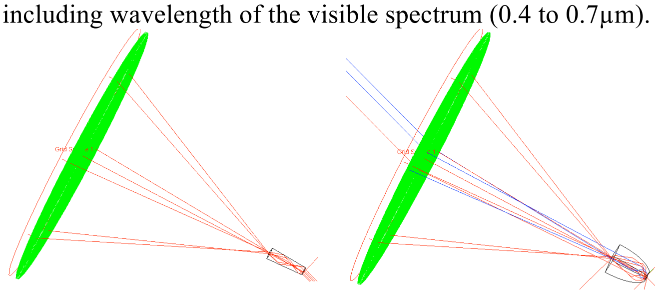


Fig. 6. Input radius of the secondary optical elements versus the refractive index

4.2. Optical performances

Comparison is performed in terms of the optical efficiency and the output flux distribution of each SOE using the above listed materials (see table 2). In each case, the SOE is firstly placed at the focal point of the Fresnel lens as indicated in fig. (7). The simulations are performed by the ray-tracing Trace-Pro software with an incident flux of 1000 W/m2 including wavelength of the visible spectrum (0.4 to 0.7µm).



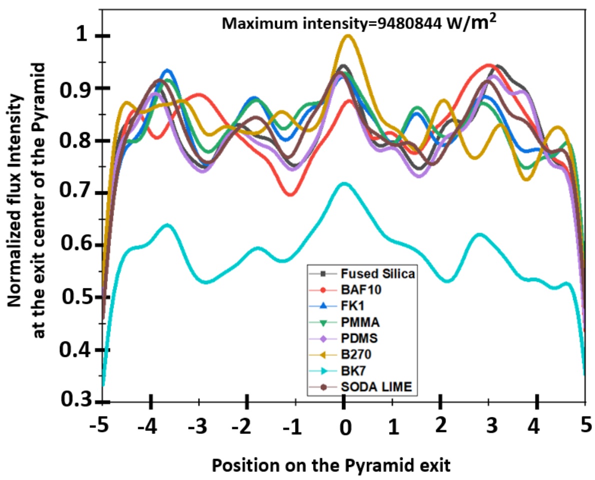
(a) Cone as SOE **(b)** CCPC as SOE

Fig. 7. Ray tracing inside SOEs at the focal of Fresnel lens

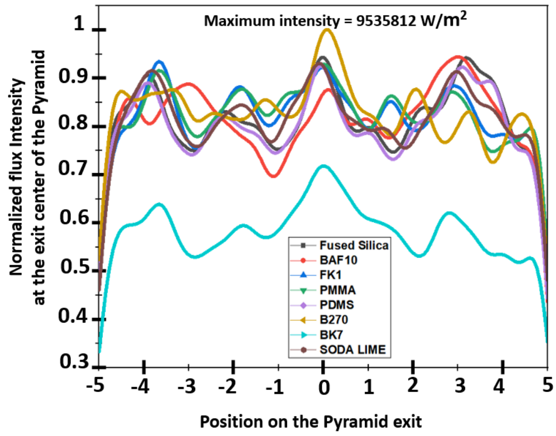
In Figures (8-11), we show the repartition of the normalized light intensity when scanning the centerline (vertical and horizontal) on the receiver obtained for the four elements. The maximal intensity is indicated, for comparison, on each figure.

Under normal light incidence, for the pyramid (fig.8), the flux density is centered around 8.5×10^6W/m^2 with some small variations. For the CCPC (Fig. 9), we observe that the flux density is centered around 3×10^5W/m^2, except for the B270 material where the intensity reaches a maximum of $5.5\text{x}10^6$W/m^2 with a less homogenous light distribution when compared to the pyramid. Regarding the CPC and the cone (circular exit), we observe a high central intensity in the receiver center, which drastically decreases while moving away to the left and right borders.

Fig. (12) shows a comparison of the whole system optical efficiencies, defined by the ratio between the flux at the entrance of the Fresnel lens and the exit of the SOE. The pyramid, the cone and the CPC show the highest optical efficiencies whatever the used material. These results must be taken with care; in fact, higher optical efficiency does not mean good uniformity of the light distribution over the receiver. The pyramid is still the best as discussed in figures (8-11). The CCPC, even having a small optical efficiency, must be considered as an interesting element. In fact this small efficiency can have several reasons among them some rays can be totally reflected and some others are subject to more reflections than their similar in the CPC, making the final intensity lower but it ensures a better homogenous irradiation on the solar cells when compared to CPC or to the cone. From this figure, we observe that the soda lime glass give the lower optical efficiency because of its low transmission. These results clearly show that the best and worst choices of materials for the SOEs manufacturing are respectively B270 and soda lime glass.

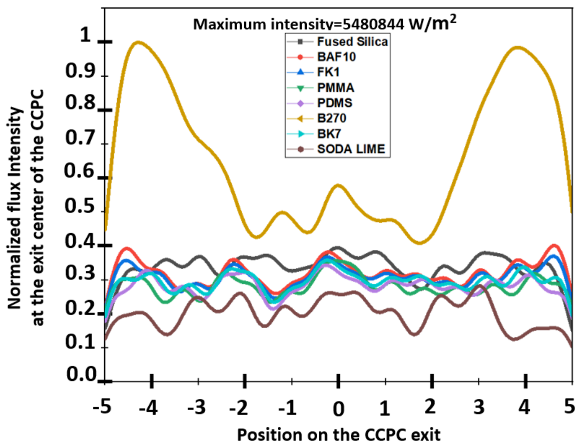


(a) Horizontal

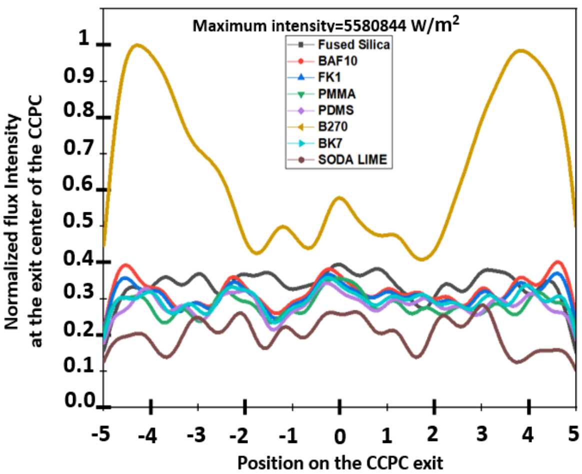


(b) Vertical

Fig.8. Repartition of the intensity at the Pyramid exit Vs material

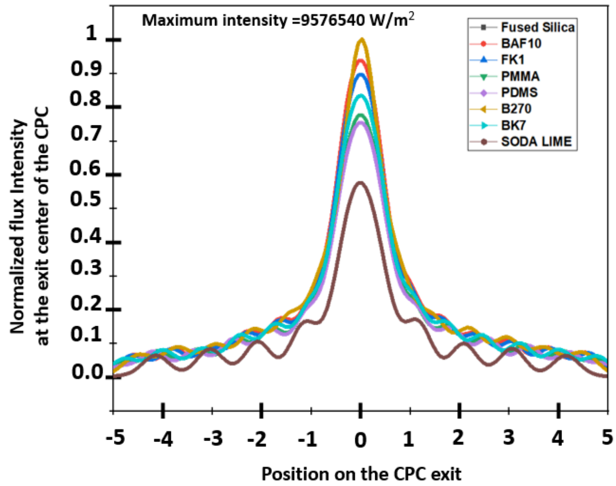


(a) Horizontal

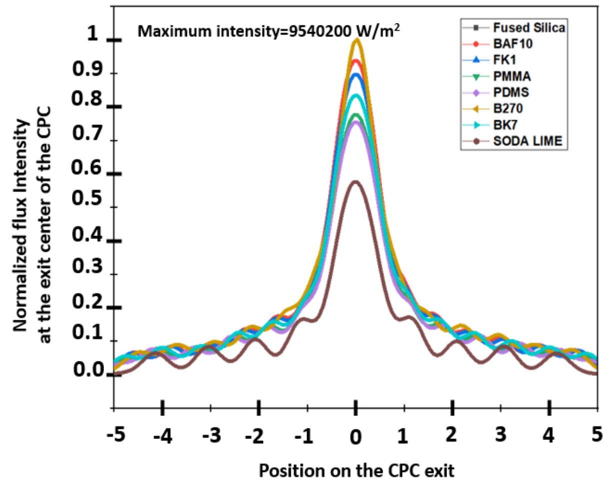


(b) Vertical

Fig.9. Repartition of the intensityat the CCPC exit Vs material

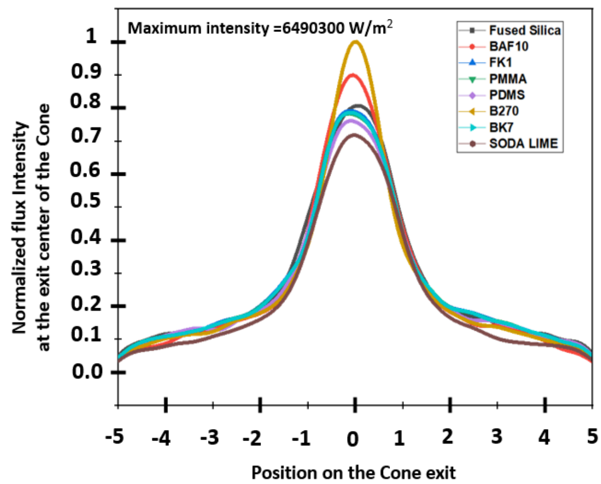


(a) Horizontal

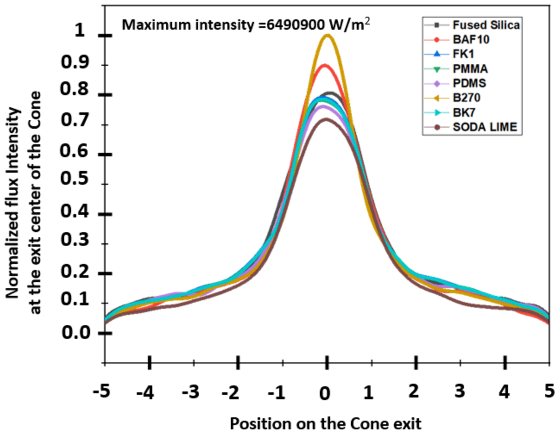


(b) Vertical

Fig.10. Repartition of the intensityat the CPC exit Vs material



(a) Horizontal



(b) Vertical

Fig.11. Repartition of the intensityat the Cone exit Vs material

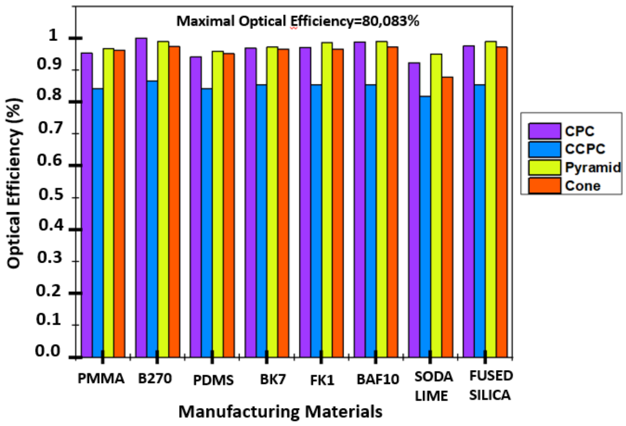


Fig.12. Optical efficicencies of the designed concentrators according to the maufacturing material

4.3. Placement of the SOEs

Here we consider only the B270 material, as this material has the best optical efficiency and it is widely available and cheaper. The main idea is to find the optimal position of the SOEs regarding the Fresnel lens.

Table 3 shows the sizes of the used SOEs, the Pyramid is designed with 2.3 reflections as determined above from fig. 5.

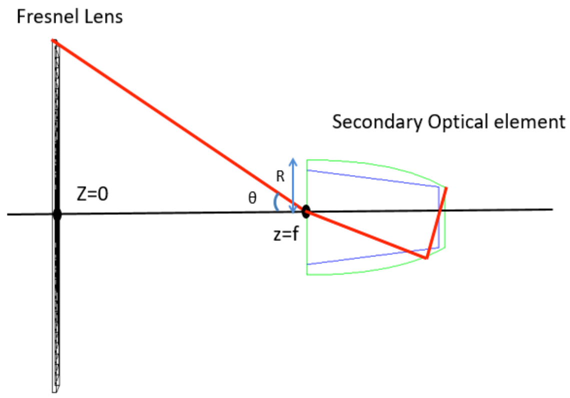
Table 3. Sizes of the SOEs (R, r and L are respectively, the input radius, the output radius and the length).

	Diameter (2R) or side length for squared shapes (mm)	Diameter (2r) or side length for squared shapes (mm)	L(mm)
CPC	27.58	10	48.30
CCPC	27.58	10	48.30
Cone	15.05	10	48.30
Pyramid	15.05	10	48.30

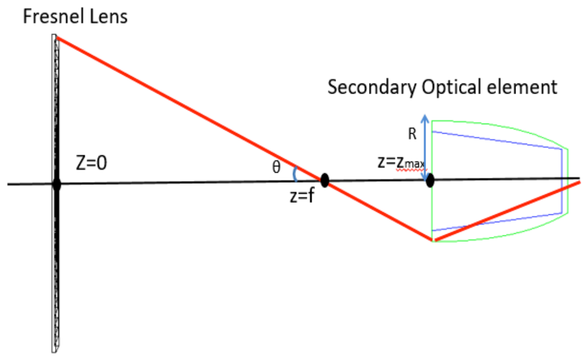
Following geometrical considerations, three possible positions are a priori possible without any optical losses: The first one, z=f, is defined by the focal point of the lens (figure (13,a)), the second and the third are $z = z_{max}$ and $z = z_{min}$, respectively defined by the place where the incoming flux size fit with the input diameter (or side) of each element beyond and before the focal point of the lens, as shown on figure (13, b) and figure (13, c). These positions are defined by:

$$Z_{max} = f + \frac{R}{\tan\theta} \quad (15)$$

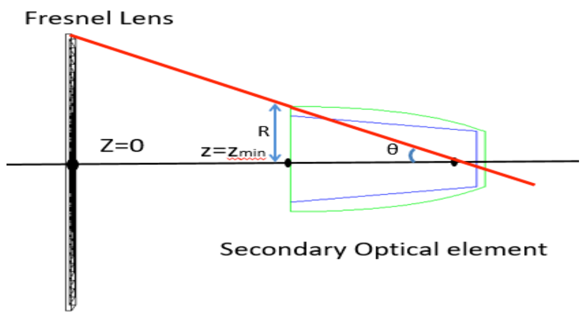
$$Z_{min} = f - \frac{R}{\tan\theta} \quad (16)$$



(a) SOE at the focal point, z=f



(b) SOE at the position maximal, $z = z_{max}$



(c) SOE at the position minimal, $z = z_{min}$

Fig.13. Position of secondary optical element

Their values have been calculated for each element and results are presented in table 4.

Table 3. Extreme position calculated for the four SOEs

	CPC	CCPC	Cone	Pyramid
z_{min} (mm)	230	230	245	245
z_{max}	300	300	284	284

(mm)				

Figures (14-17) illustrate typical flux distributions at the exit of the studied SOEs depending on their placement between these extreme limits. Here we present only the horizontal scan, giving that the vertical one is the same.

For the pyramid, the flux is homogenous with the best homogeneity at z = f. At $z = z_{max}$, the flux shows the same behavior as the CPC and the Cone with a central intense peak.

For the CCPC, the light distribution is only homogenous in the focal point, far from this position toward $z = z_{min}$ we observe an intense central peak as the other SOEs, and toward z_{max} the peak splits into two intense parts around the center of the receiver.

For the CPC and the Cone, the flux is rather concentrated in the middle of the receiver, with an intense peak. At $z = z_{max}$, this peak becomes larger but with a slightly lower intensity than at the position z = f.

Figure (18) shows the variations of optical efficiencies of the four systems versus the relative position to the lens of the SOEs. It is clear that the optical efficiency in each case starts by increasing, and becomes constant over 35 mm for the CCPC and the pyramid, and 20mm for the cone and the CPC, then its decreases when approaching to the maximal distance from the lens $z = z_{max}$. The pyramid and the CPC are still keeping the higher efficiencies.

Another selection criterion for concentrator is its acceptance angle, defined as the angle where the optical efficiency falls to 80% of its initial value [7]. For this, we have performed simulation by varying the incidence angle from 0° (normal incidence) to 1.4° (actual most solar tracker precision).

Figure (19) resumes these variations of the acceptance angle of the whole systems (FL+SOE) measured when the efficiency fall to 80% of their initial values. Those results show that the CPC presents the largest one (1.4°) for all positions. The pyramid only reaches this angle from 250mm to z_{max}. Even if the pyramid presents a large acceptance angle from 250mm to z_{max}, the flux is more uniform at z = f, which is a more adapted position for uniform cell irradiation and cell heat limitation.

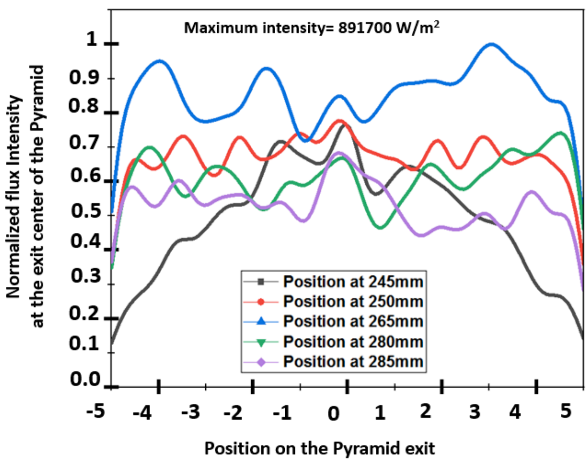


Fig.14. Repartition of the intensity at the Pyramid exit Vs position

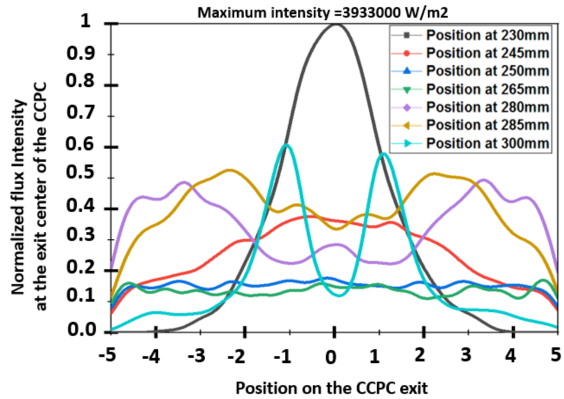


Fig.15. Repartition of the intensity at the CCPC exit Vs position

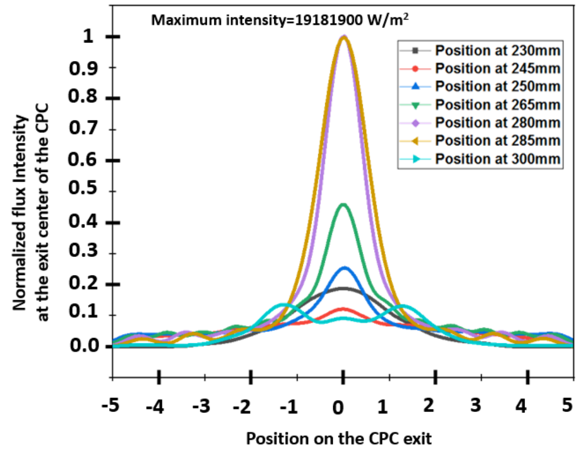


Fig.16. Repartition of the intensity at the CPC exit Vs position

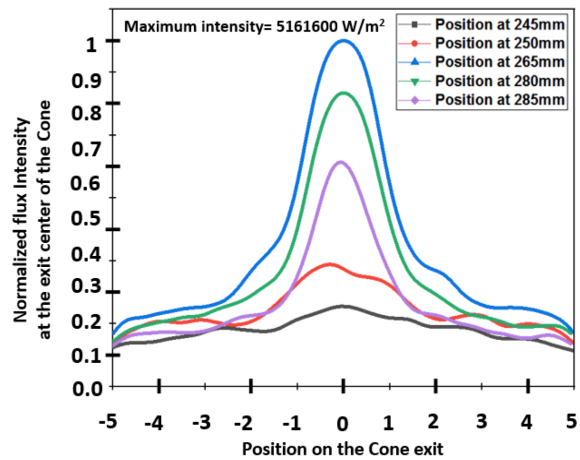


Fig.17. Repartition of the intensity at the Cone exit Vs position

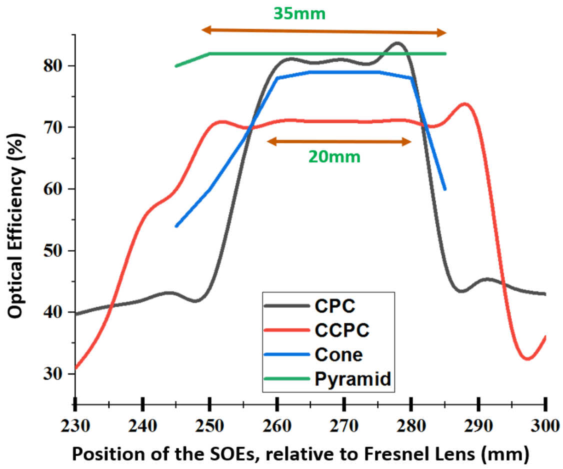


Fig.18. Optical efficiencies at several positions of the SOE away from the lens (mm)

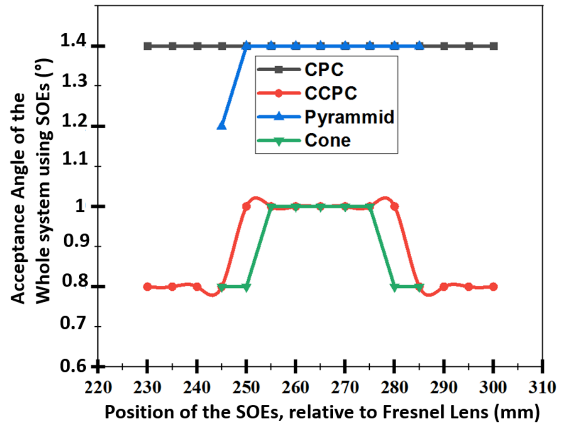


Fig.19. Acceptance angle at several positions of the SOE away from the lens (mm)

Finally, some additional tests configurations were performed in order to valid and to generalize the study results. The first test concerned the focal distance of the lens. We have varied the focal length of FL from 175mm to 700m. The second concerned varying the facet spacing from 0.1 to 1mm with a step of 0.1mm. The last test was dedicated to wavelengths variations from 0.1 to 1.4µm. All these simulations results show the same hierarchy in the performances of the studied SOEs.

We found at each time that the CPC has the worst homogeneity even it has the highest intensity, however, the pyramid has high optical efficiency as CPC and the best homogeneity when compared to the others elements.

At the end, our results show that the choice of the SOE is not so easy given the several and sometimes opposite constraints. Regarding the flux uniformity and the higher optical efficiency, the choice is undoubtedly the pyramid whatever the lens characteristics and the manufacturing material; however, the acceptance angle is the largest for the CPC with non-uniform flux distribution at the end. The same trends concerning the flux homogeneity were reported by Victoria et al. who compared four secondary optical elements made from metal [7] and with an aspheric lens as a POE. However, our system shows a largest tolerance angle even for the pyramid. Moreover we highlight a clear dependence of the SOEs on the refractive index of the used materials, different lens characteristics and we investigate the better placement for each SOE in relative to the focal point of the Fresnel lens.

To easiest the comparison between all these optical secondaries, a figure of merit, presented in figure (20), is proposed taking into account the main characteristics of each element (optical efficiency, flux homogeneity, acceptance angle and the placement tolerance). The maximal value of each parameter is used to normalize the others. For the uniformity, we just scaled from the best to the worst case. We can observe that the pyramid is the best concerning the relative best scores.

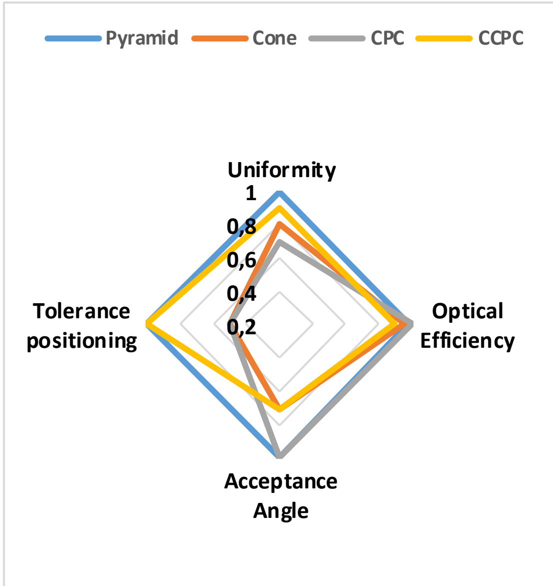


Fig.20. Comparison of the performance of four CPV systems using SOEs

5. Conclusion

We have presented in this paper a parametric and detailed comparison of the performances of four CPV optical systems formed by CPC, CCPC, a Cone and a Pyramid as secondary optical elements with a Fresnel lens as the primary optic.

Results show that the length and the input radius of the four SOEs increase with the increment of the refractive index. In this case, designers have to be aware about the number of reflection to fix the size of their systems given that it depends highly on the refractive index.

We have also seen that the pyramid gives the more uniform irradiance distribution and the higher optical efficiency whatever the characteristic of Fresnel lens or used material. The CPC gives the higher optical efficiency but the worst homogeneity. The systems optical efficiencies are higher at the focal point of the lens, which gives some tolerances in the mechanical fixation of the systems. Concerning the system tolerances of the ray deviations, the CPC still having the larger acceptance angle but in this case the receiver is not homogeneously irradiated.

For the pyramid, the flux is homogenous with the best homogeneity when placed at the focal point on the FL.

From this study, we then can clearly claim that the pyramid constitute the best choice of the secondary optical element for the considered CPV system and the B270 corresponds to the best material choice to manufacture the SOE.

To generalize the study several scenarios with a Fresnel lens having different characteristics has been tested and a hierarchical choice is proposed for the CPV users.

A figure of merit is proposed for a quick comparison between all the studied elements.

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