

# Performance analysis of non-imaging Fresnel lens as a primary stage for CPV units

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**Abstract.** *Fresnel lens is widely used in concentrating photovoltaic (CPV) systems as a primary optical element. It focuses sunlight on small solar cells or on the entrance apertures of secondary optical elements. In this work, we present a performance analysis of a non-imaging Fresnel lens as a primary optical element for different values of focal length. Results show , among others, the necessary use a secondary stage of concentration in order to achieve good performances in terms of the uniformity of the flux and a large acceptance angle compared with those of a Fresnel lens used alone.*

## 1. Introduction

In recent years, concentration photovoltaic systems have attracted more interest of industrials and researchers working in the field of renewable electricity. These systems needs optical elements to focus direct sunlight onto multi-junction solar cells that have record efficiencies above 44% [1] . There are generally two optical elements in CPV modules: a primary and a secondary elements. The primary is used to collect the sunrays, and the secondary, placed near the receiver, is used to redirect the sunlight onto the cell as well as to improve the energy uniformity.

Two types of optical elements can be used as a primary optical element. Mirrors [2] [3] [4], and Fresnel lenses [5]. The gains that can be achieved with a Fresnel lens or a parabolic mirror were previously compared [6]. Even more, results coming from each way still comparable and the two configurations were developed competitively. In the case of a system using a Fresnel lens, the chromatic aberration phenomenon causes non-uniformity of the concentrated distribution on the solar cell surface [7]. Localized hot spots and non uniformity increases the cell temperature, cell resistance, and lowers the efficiency. Secondary optics helps to solve this problem and 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.

In the present work, inspired by the work of Kwangsun Ryu-et-all [8] who analyzed the performances of Fresnel lens only for the low concentrations ratio, we propose to extend the study to the high concentration levels. Deep analysis of the performances of the Fresnel lens highlights the necessity of using a secondary optical element, the pyramid here. The considered



Fresnel lens is assumed to be manufactured from PolyMethyl MethAcrylate (PMMA). The concerns of discussion are the flux homogeneity on the receiver, the optical efficiency and the acceptance angle. All our results are performed by simulation using the ray tracing TracePro software.

## 2. Concept and design of Fresnel Lens

For an optical concentration system as shown on fig. 1, the geometrical concentration is given by [9]:

$$C_{geo} = \frac{a^2}{a'^2} = \frac{n_2^2 \sin^2 \theta_f}{n_1^2 \sin^2 \theta_s} \quad (1)$$

$n_1$  and  $n_2$  are the refractive index of the entrance and exit medium respectively,  $a$  and  $a'$  are the entry and the exit area of the concentrator system,  $\theta_s$  and  $\theta_f$  are the angles of incoming and outgoing beams respectively. For solar systems,  $\theta_s$  corresponds to the half angular aperture of the sun.

The Fresnel lens consists of several prism rings [10] arranged as shown in fig.2a.

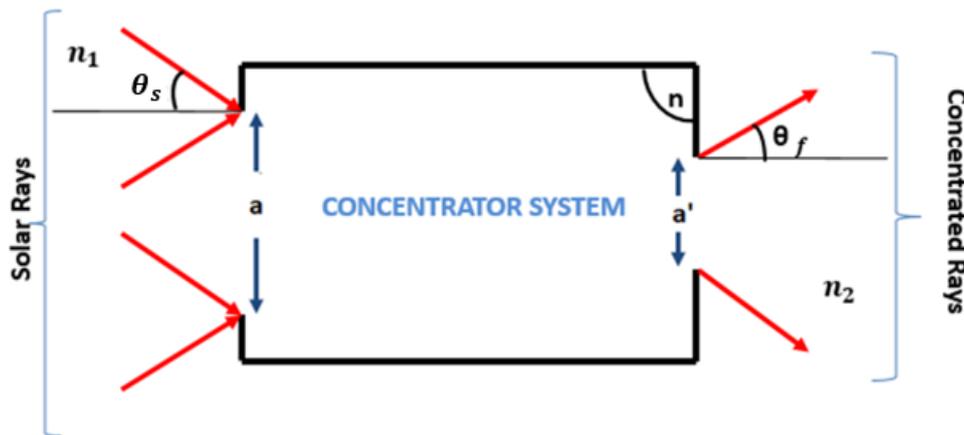


Fig.2b shows a single prism a typical the path of a light ray.  $r_p$  and  $r'_p$  are respectively the angles, to the surfaces normal, formed by the refracted ray at the entrance of the prisme and the incident at its exit,  $\beta_p$  is the angle of the refracted ray,  $\theta_s$  is the incidence solar angle and  $f$  is the focal length of the Fresnel lens. Each prism  $p$ , of the lens is described by the following equations [11]:

$$\sin \theta_s = n \sin r_p \quad (2)$$

$$n \sin r'_p = \sin \beta_p \quad (3)$$

$$\theta_p = r_p + r'_p \quad (4)$$

$$\beta_p = \theta_a + r'_p \quad (5)$$

$$\tan \theta_a = \frac{d}{2f} \quad (6)$$

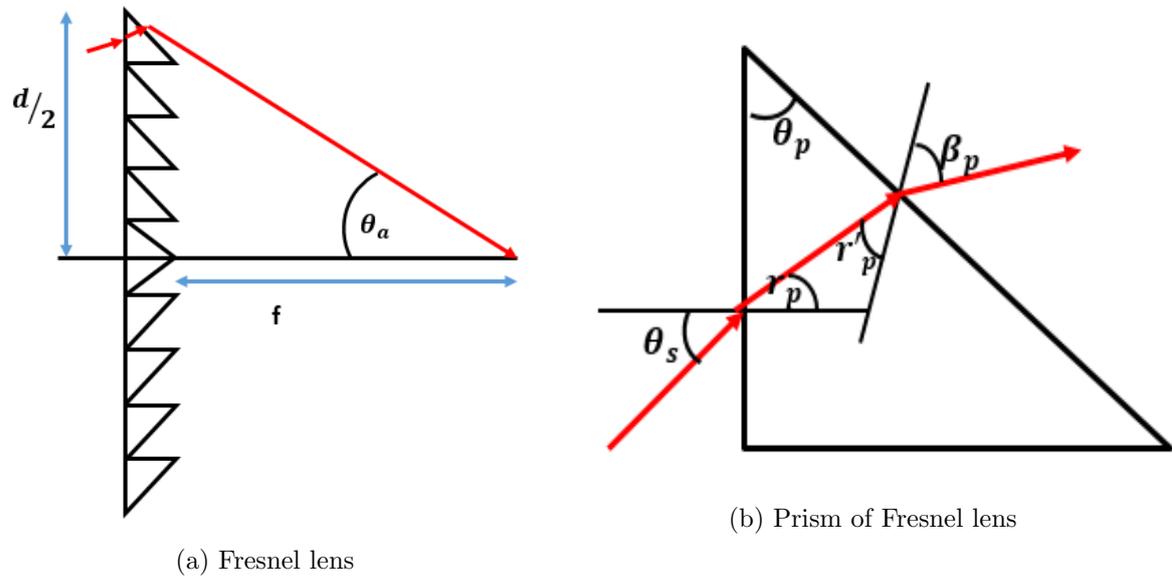


Figure 2: Design of Fresnel Lens

From the angle of the prism  $\theta_p$ , and using the equations 2,3, 4 and 5, it is therefore possible to determine the angles of refraction  $\beta_p$  and the opening angle  $\theta_a$  of the Fresnel lens. Fig.3 shows the variations of both the opening angle of the Fresnel lens and refraction angle of each prism  $\theta_a$  and  $\beta_p$  as a function of the angle of the prism  $\theta_p$  for a refractive index  $n_f = 1.493$ . This figure illustrates that the incidence angles of the Fresnel lens is limited to  $45^\circ$  as a function of the prism angle. This is due to the reflection which undergo the rays once the refraction angle of each prism  $90^\circ$  is reached.

For an accurate simulation, refractive index data,  $n(\lambda)$ , versus wavelength  $\lambda$  is desirable. in

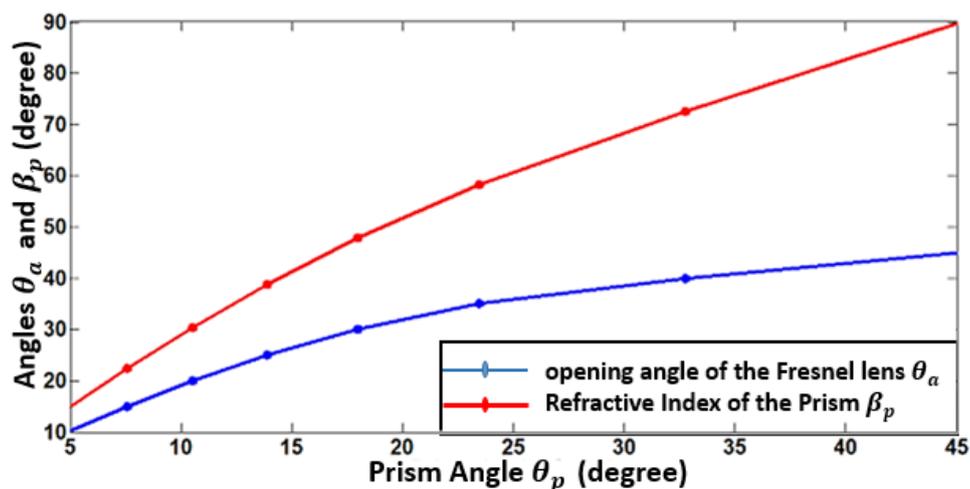


Figure 3: Opening angle  $\theta_a$  and refraction angle  $\beta_p$  as a function of the angle of the prism  $\theta_p$  for a refractive index  $n_f = 1.493$

the range or interest, in this case, from  $0.4$  to  $0.7\mu\text{m}$ . Refractive index values are taken from the

model reported in [12] for PMMA. In fig.4, we can see that the refractive index decreases with the increment of the wavelength and we get for  $n_f = 1.49$ ,  $\lambda = 0.5\mu\text{m}$ .

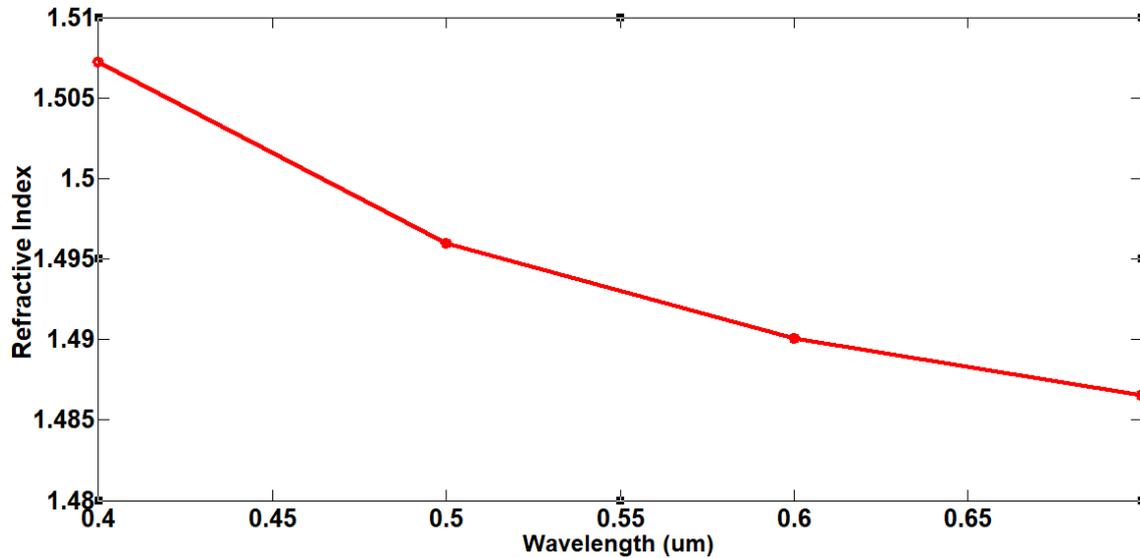


Figure 4: Refractive index characteristic of PMMA used in the simulations

### 3. Results and Discussions

#### 3.1. Optical Performances of the Fresnel lens

The first test concerns the effect of the focal length of the Fresnel lens  $f$ , on the flux distribution, the optical efficiency and the acceptance angle. For that, The lens used in this study is a typical a circular Fresnel lens made of PMMA with a diameter of 350mm and the ring facet spacing is 0.38mm. The considered receiver is a squared form of 10mm side, and we varied the focal length of Fresnel lens, made from PMMA, from 175mm to 700mm. Fig. 5 presents the evolution of the flux distribution with the variation of the Fresnel focal length. We notice that the focal length has a big effect on the spot diameter, the spot diameter increases with the increment of the focal length as describe eq.7 with  $D_s$  being the spot diameter and  $\lambda$  is the wavelength.

We also notice that the flux distribution can be more uniform if the focal is very long but it will make the CPV system bigger and very wider. This is a new added constraint to the designed panel design.

$$D_s = 1.22 \frac{\lambda}{\sin \theta_a} \quad (7)$$

As we target a good homogeneity with a higher optical efficiency, we investigate the effect of a secondary stage which is the pyramidal cone in the next part of this work.

#### 3.2. Effect of a secondary stage

The integration of secondary optical elements into a CPV system must allows for higher tolerances in the system and homogenize the irradiance on the solar cell, then for that, we proposed the pyramid as secondary stage made from Fused silica with its aperture exit fixed

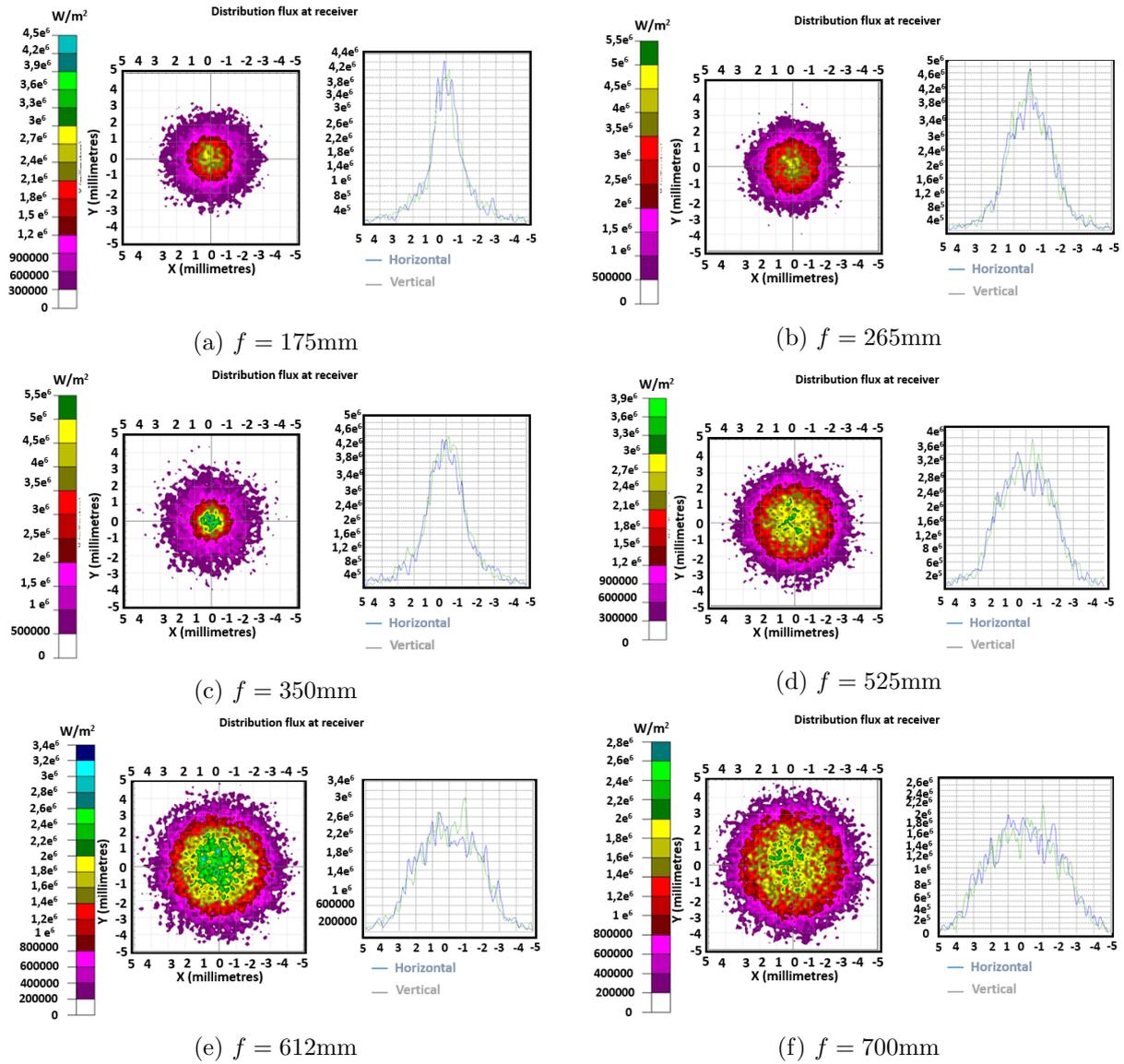


Figure 5: Evolution of flux distribution vs Fresnel lens focal length

to 10mm. This secondary is associated to the same Fresnel lens studied above. The geometry of the pyramid (fig.6) is inspired from its resemblance to the cone; it is defined by the output and input radius  $r$  and  $R$ , the output and input angle  $\theta_f$  and  $\theta_a$ , the angle of pyramid  $\alpha$  and its length  $L$  [2]. The length of the pyramid depends on the inside number of ray reflections,  $N$ . These parameters are dependent and are related by the following equations [2]:

$$\theta_f = \theta_a + 2N\alpha \quad (8)$$

$$R = r + \sum_1^N a_N \quad (9)$$

$$L = \frac{\sum_1^{N+} a_N}{\tan \alpha} = \frac{R - r}{\tan \alpha} \quad (10)$$

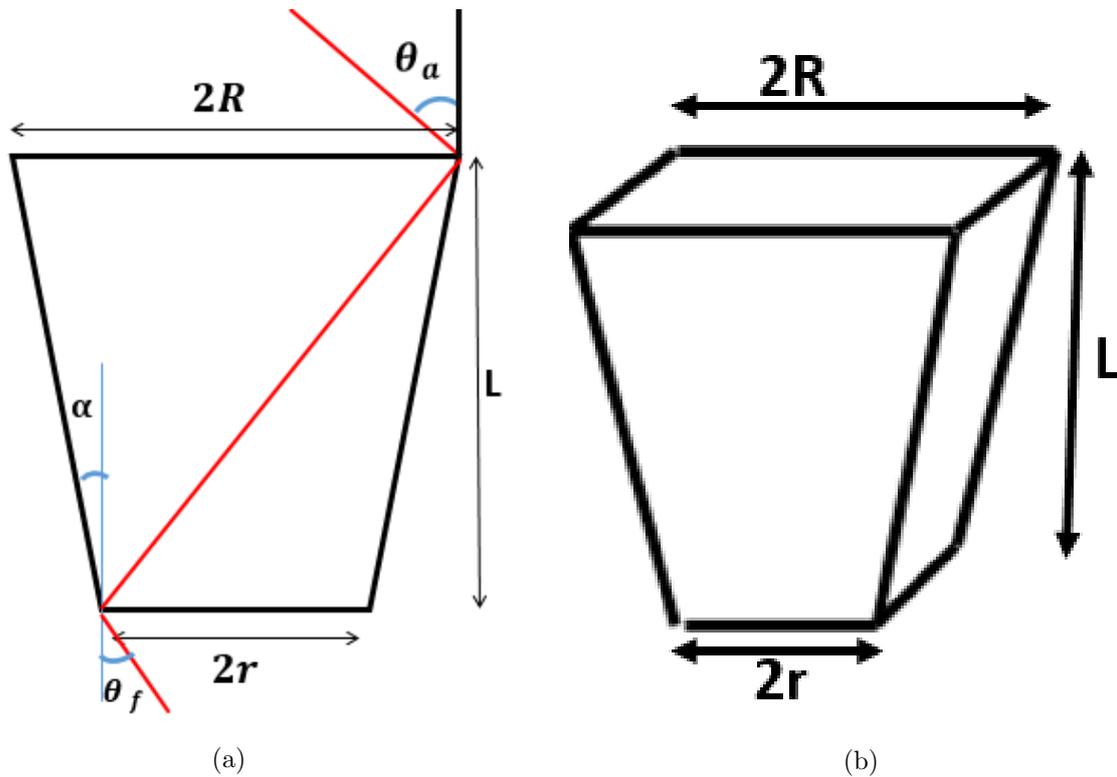


Figure 6: (a) Section of the Pyramid (b) 3D-view of a pyramid

By varying the focal length of the Fresnel lens and using the equations (7, 8 and 9, we obtain the pyramid input diameter  $2R$  evolution as shown on Fig.7. The maximum value of  $2R$  tends to 15mm for very large focal distance  $f$ , of more than 1m. which is too large for a convenient CPV setup. Fig. 8 shows the net improvement of the flux homogeneity on the exit of the pyramid for different focal length of Fresnel lens compared to the flux distribution observed on fig.5. The flux is distributed on the whole exit of the pyramid, however, it starts by a high peak in the center, and becomes more uniform with the increment of the focal length of the Fresnel lens until  $f = 700\text{mm}$  and starts to be inhomogeneous again .

Fig.9 shows a comparison of the optical efficiency, for the two optical systems: The Fresnel lens and the Fresnel lens associated with the pyramid. We notice that the optical efficiency of the system using only the Fresnel lens, increases with the increment of the focal length until  $f = 600\text{mm}$  and start to decrease whereas for, the second system, with two stage of concentration, it starts by increasing and becomes stable from 350mm.

Table 1 resumes the effect of focal length and the secondary element on the acceptance angle of the optical system, we notice also that we get a large acceptance angle in the case of short focal length, and this acceptance angle becomes largest when the secondary stage is used as shown in the table 1.

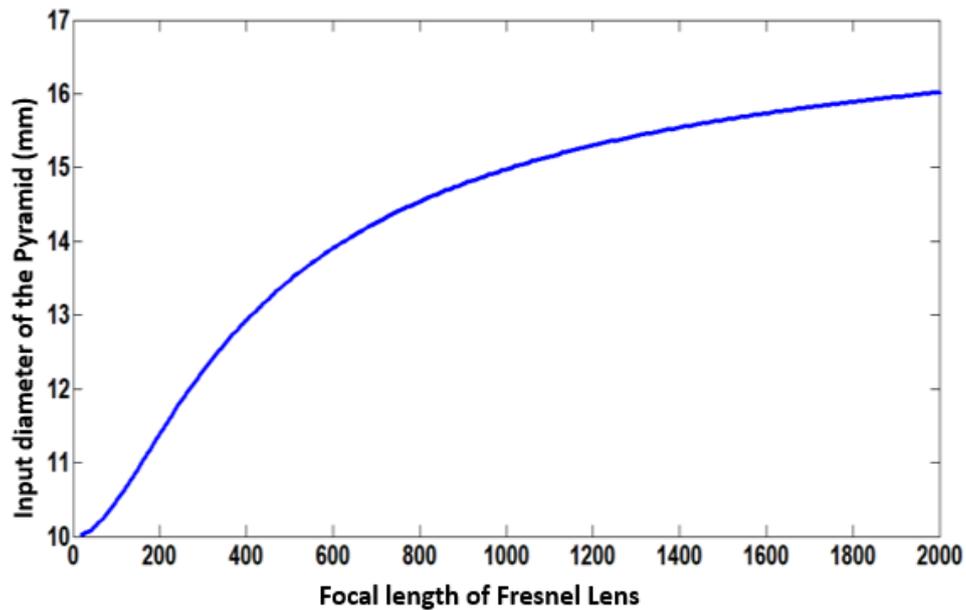


Figure 7: Input diameter  $2R$  of the pyramid versus focal length  $f$ , for a Fresnel lens diameter of 350mm

Table 1: Acceptance angle variation versus the focal length

	175mm		350mm		700mm	
	Optical Efficiency in (%) at $0^\circ$	Acceptance angle ( $^\circ$ )	Optical Efficiency in (%) at $0^\circ$	Acceptance angle ( $^\circ$ )	Optical Efficiency in (%) at $0^\circ$	Acceptance angle ( $^\circ$ )
Fresnel lens	56.58	0.6	86.566	0.4	88.3	0.2
Fresnel lens + Pyramid	51.4	1	86.27	0.8	88.29	0.4

#### 4. Conclusion

A comparative study of the CPV system performance composed of the Fresnel lens alone and CPV system composed of the same Fresnel lens associated with the pyramid as secondary optical element is performed. We found that the secondary optical element has an important rule to improve the homogeneity on the solar cell, and allow for high tolerance. We found also that the focal length decreases the acceptance angle whatever the configuration of the CPV system.

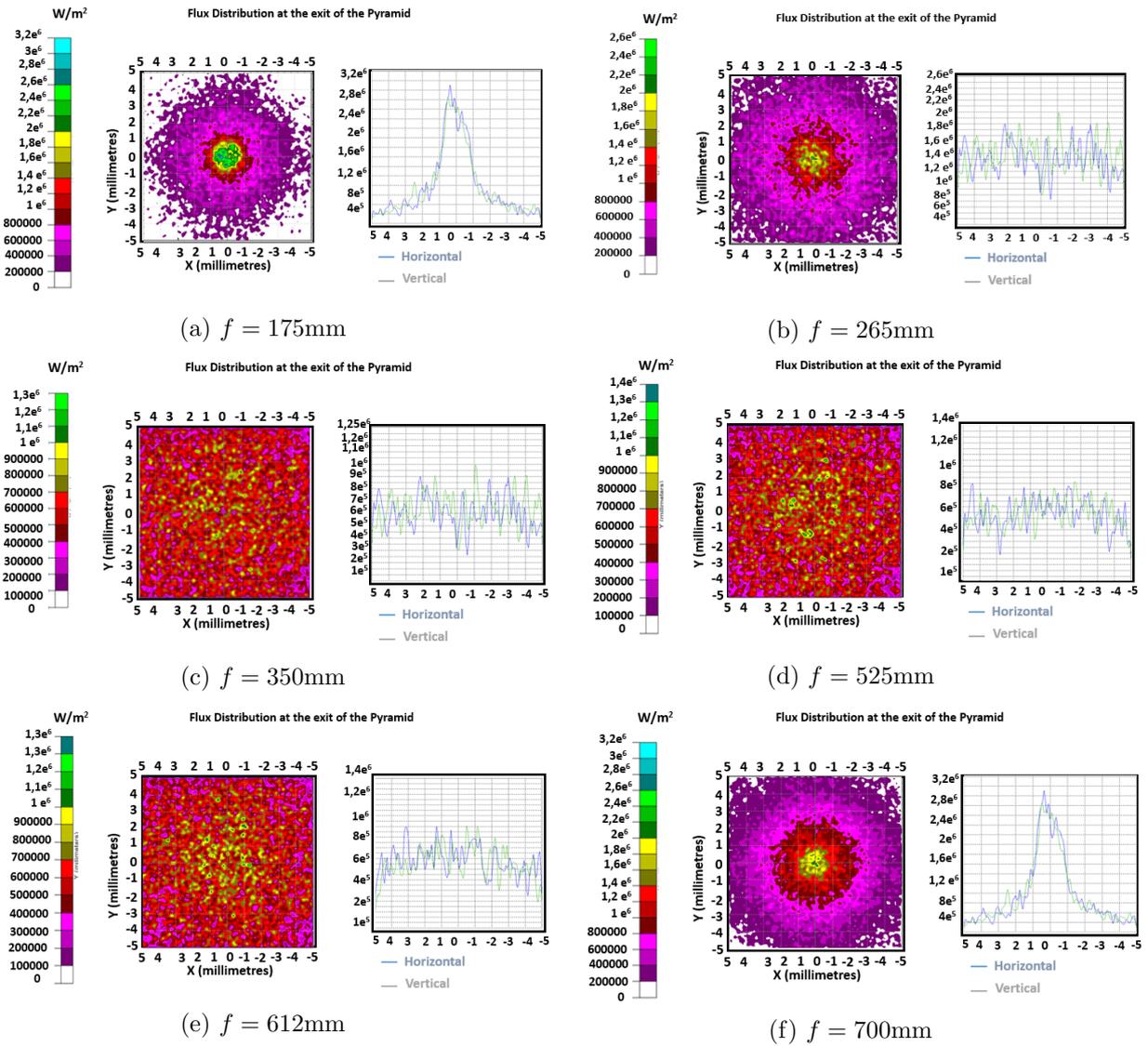


Figure 8: Evolution of flux distribution using two stages of concentration

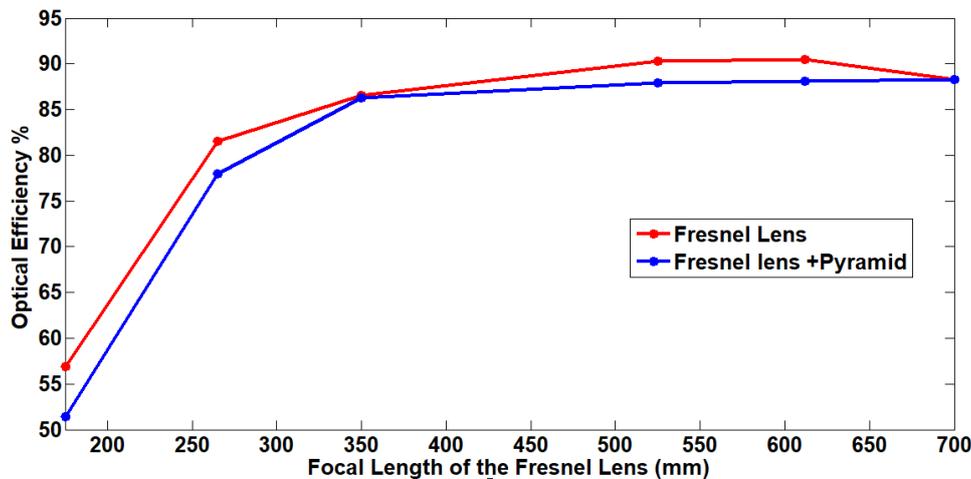


Figure 9: Evolution of the Optical Efficiency of the two CPV system vs Fresnel lens focal length

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