MINI-SOLAR FURNACE BY USING A POINT FOCUS SOLAR CONCENTRATOR

C.A. Pérez-Rábago [1], D. Riverso-Rosas [3], O.A. Jaramillo [1], M. Bazán [2], M. Carrillo-Santana [1], M. Montiel-González [1], G. Ascanio [2], C.A. Estrada [1]

[1] Centro de Investigación en Energía, Universidad Nacional Autónoma de México,
Priv. Xochicalco s/n, Temixco, Morelos, 62584 México.
[2] Centro de Ciencias Aplicadas y Desarrollo Tecnológico, Universidad Nacional Autónoma de México,
Apdo. Postal 70-186, 04510 México D.F., México
[3] Instituto de Geofísica, Universidad Nacional Autónoma de México,
Ciudad Universitaria s/n, Ciudad de México, D.F., 04510 México.

Abstract

The paper presents the technical modifications of DEFRAC (Spanish acronym for Device for the Study of Highly Concentrated Radiative Fluxes) in order to obtain a mini-solar furnace (MSF). DEFRAC is placed in vertical position and the optical arrangement of facets is oriented viewing to the north. A small flat heliostat system with 5.6 m^2 of surface area was designed and constructed to track the movement of the sun and redirect sunlight along to the optical axis of the fixed DEFRAC the concentrator. The reflective surface of the heliostat is obtained by using a flat mirror with a tolerance lesser than 1 *mrad.* The MSF has a shutter with an area of 2.56 m^2 that attenuates the solar energy reflected by the heliostat. In this paper we present the preliminary result of the optical performance for the MSF and the evaluation of the track system of the heliostat and the control of the shutter. The MSF will be used in the development of different kind of studies; from studies of heat transfer in open small cavities to the development of small receivers.

Keywords: Heliostat, Shutter, Solar concentrating system, mini-solar furnace.

1. Introduction

In 1995, a solar concentrating system named DEFRAC (Spanish acronym for Device for the Study of Highly Concentrated Radiative Fluxes) [1, 2] was developed at The Centre for Energy Research of the National Autonomous University of Mexico. This device was developed in order to support basic and applied research on solar concentrating technologies. DEFRAC was designed as a point focus solar concentrator with an equatorial solar tracking system. It consists of two frames: one of them is used as the main structural support and the other one, that is a structure with hexagonal shape, holds 18 first surface parabolic mirrors. Each mirror measures 30 cm in diameter and they are made of aluminized glass with an average reflectivity of 0.95 over the solar spectrum. The 18 mirrors are grouped in three sets of six mirrors each, named A, B and C. The difference between the three sets of mirrors is the focal length with values close to 2 m. The total area of the reflectors is 1.27 m^2. Figure 1 depicts: a) a schematic representation of the DEFRAC, b) the sets of mirrors and the absorber device for concentrated solar energy, and c) a picture of DEFRAC and the focal spot.

DEFRAC was designed to obtain a spot with 2.5 cm in diameter with a mean concentration close to 3000 suns, and a solar concentration peak above 4750 suns. DEFRAC has being used for several successfully studies, as the development of solar flux measurement instruments [3,4].

In a previous work, the theoretical an experimental distribution of concentrated solar flux in the spot was obtained. Figure 2 shows these distributions of DEFRAC. In both cases, the distribution of concentrated solar flux has been normalized. By considering the radial distribution of the incident solar energy (sunshape) σ_{sun} and the intrinsic optical errors $\sigma_{optical}$, the experimental results shown that the total beam width σ_{tot} is 6.5 mrad, it is calculated by using equation (1),

$$\sigma_{tot} = \sqrt{\sigma_{sun}^2 + \sigma_{optical}^2} \qquad (1)$$

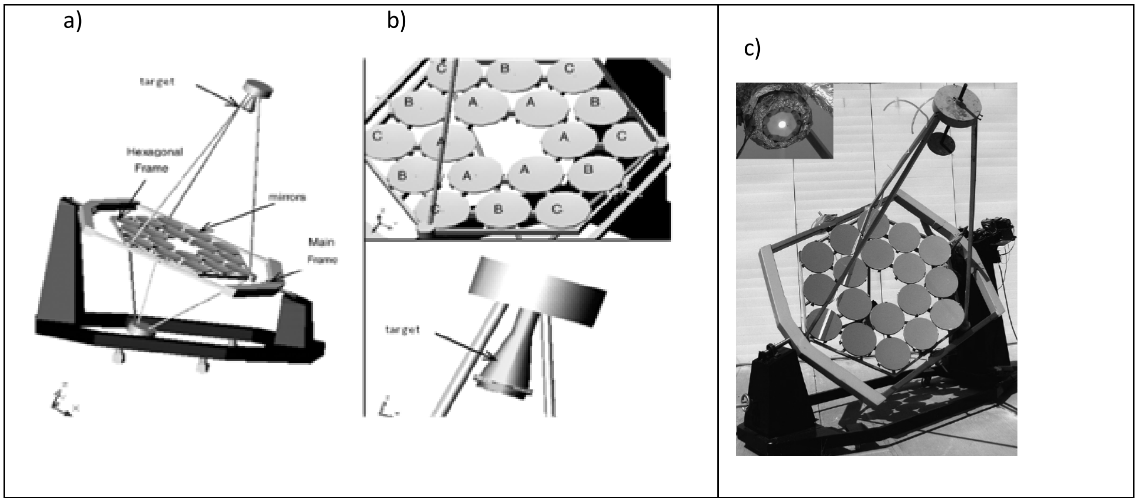

Fig 1: Schematic view and picture of DEFRAC

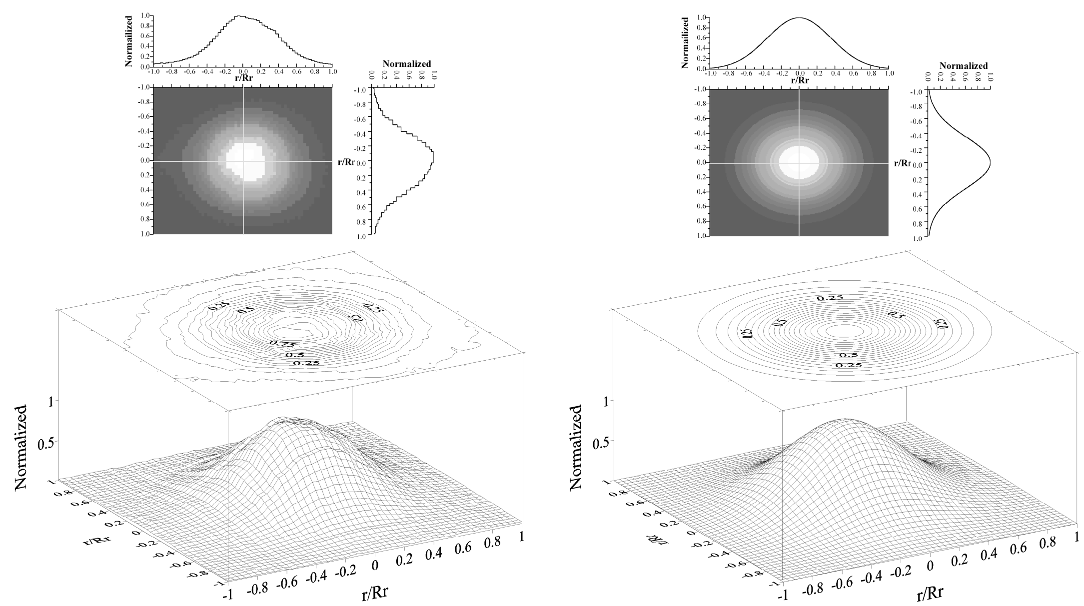

Fig. 2: Spatial distribution of the concentrated solar flux in the receiver,

experimental (left) and theoretical (right).

The mathematical model that describes the radial distribution of concentrated solar flux in the spot is established by [5],

$$G(r) = \pi f^2 \rho_r G_b F_A (cos^2\varphi_r - cos^2\varphi_{min}) \frac{\mathrm{a\,exp}\left(-\mathrm{a}\left(\frac{\mathrm{r}}{\mathrm{R_{spot}}}\right)^2\right)}{\pi \mathrm{R}^2_{\mathrm{spot}}(1-\exp(-\mathrm{a}))} \tag{2}$$

where f is the focal length of DEFRAC close to 2.00 m, ρ_r is the reflectivity of the mirrors of DEFRAC, G_b is the solar beam radiation, F_A is an area factor that takes into account the actual collecting area of the DEFRAC, φ_{min} is the angle formed by the optical axis of the DEFRAC and the inner edge of the mirrors, φ_r is the angle between the optical axis of the DEFRAC and the outer edge of the mirrors, $R_{spot}[m]$ is the diameter of the spot , and the amplitude distribution coefficient a[-] is estimated by

$$a = \frac{R_{spot}^2}{2(\sigma_{sun}^2 + \sigma_{optical}^2)} \quad (3)$$

From experimental results it is possible to obtain that the parameter *a* can be estimated between 1.52 and 2.35 for DEFRAC. Note that the experimental results depend on the sunshape for different sunny days in approximately 3.6 < σ_{sun} < 5.6 mrad.

To achieve the concentration distribution shown in Figure 1, a proper alignment of the 18 mirrors of the DEFRAC and a precise tracking of the Sun are required; however, structural deformation of the hexagonal frame throughout the motion of the solar tracking system, may cause that some of the mirrors became misaligned and therefore the spot size could increase reducing consequently concentration rate on the surface of the solar receiver. On the other hand, the DEFRAC has a structure with three bars that form a tripod, which is fixed over the hexagonal frame (see Figure 1). This structure works as a support for the receiver in the DEFRAC focal area at a distance of 2.027 m above the main frame, as can be seen in figure 1.

Being the DEFRAC a point source concentrator with a solar tracking movement, the receiver is always subject at a force in the direction of motion. This force may affect the flow of fluids entering and leaving the receiver, for example, the performance of the coolant fluid. In such case or other cases, it is better to have the receiver in a fixed position during operation of the solar concentrator. To this end, it is proposed to have a stationary solar concentrator, complemented with a shutter and a heliostat; such combination is named Solar Furnace.

In order to convert the DEFRAC into a mini solar-furnace (MSF), the main structure and the hexagonal frame are fixed in such a way that are parallel to each other, and placed at 90° with respect to ground. All three components must be aligned in the north-south direction, as shown in Figure 3.

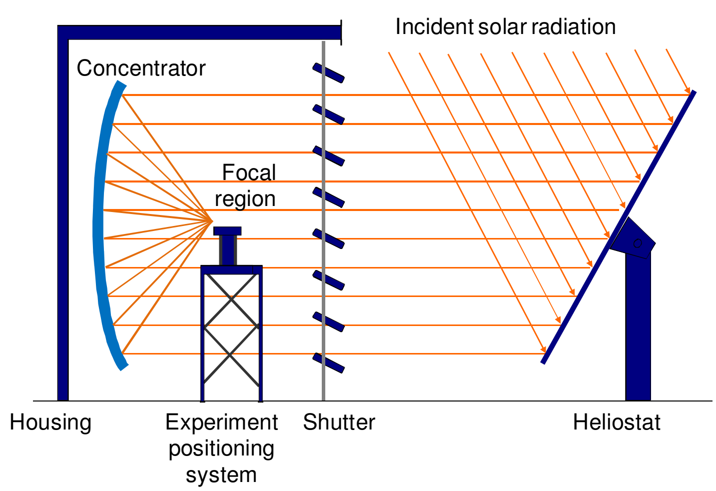

Fig. 3. A schematic of a Solar Furnace and its components.

2. The Heliostat

The heliostat for the MSF has to work at least 4 hours around the solar noon all over the year. Therefore, its design will ensure during this time that the sun's radiation beam reflected from the heliostat will cover all the mirrors of the concentrator, which are circumscribed in a square 1.6 m side. The MSF will be operated at the latitude of Temixco, Mexico: 18° 50' 20.81'' N, which is below the Tropic of Cancer; at this latitude in the summer solstice at June 21st, the solar trajectory passes 4.5° north of zenith. The summer solstice was chosen as a design parameter because it represents the maximum declination of solar path during the year. At such date the heliostat must have an inclination of 47.5° at solar noon to illuminate all the mirrors of the concentrator; therefore, at that angle, the face of the heliostat is estimated to have a reflective area of 5.6 m^2, that is to say, a square with 2.36 m side.

On the other hand, the point of rotation of the heliostat must be coincident with the optical axis of the concentrator, which is located at 1.35 m above ground, as shown in Figure 4.

Fig 4: Esquema y fotografía del helióstato de 5.6 m^2 del MSF

The transmission mechanism of the heliostat was designed by using a couple of commercial motor-transmission, with a high gear ratio (10,000:1). The axes of transmission are coupled considering an angle of 90°. The transmission for the azimuth movement is fixed to the pedestal of the heliostat and the axis of the crown is attached to a bearing box. The arms of the heliostat support the structure where is placed the mirrors. The heliostat consists of 4 square mirrors with a thickness of 6 mm and reflectivity of 0.86. Each mirror offers an area of 2.89 m^2 and the total projection area is 5.6 m^2. The mirrors of the heliostat are placed to a square frame of 0.36 m^2 and they are attached with an elastic polyurethane adhesive with a resistant of 16 kg-cm^{-2}. It is important to indicate that the frame of the heliostat has been rectified with a tolerance of $\pm$0.1 mm to ensure the flatness of the reflection surface.

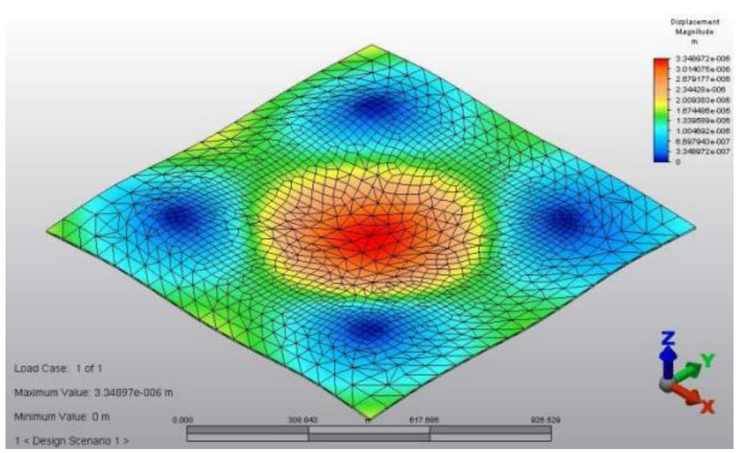

Fig 5: Deformation modelling on the face of the MSF heliostat.

In order to evaluate the heliostat mechanical deformations caused by gravity force and the load of winds up to 20 km/h, a finite-element modelling was developed. The modelling was performed considering the four support points of the frame on each end of the heliostat face (see figure 5). The result of modelling indicates that the maximum deformation occurs at the centre of the facet with a displacement of 3.3 mm, as can be seen in Figure 5. This implies a ray deviation error of less than 1 mrad, which is within the global optical error of the system.

3. Shutter

The shutter allows controlling the solar flux energy reflected by the heliostat and it is also used as protection equipment since it is possible to close the shutter very fast during a contingency. The size of the shutter is established by the shadow that is projected on the concentrator; therefore the shutter offers a square area with 1.6 m by side. The shutter consists of 12 sheet made in steel with a thickness of 1.6 mm and a width of 16 cm. Each element of the shutter is placed in a vertical position with an overlap of 1 mm. The elements are articulated in top and the bottom of the frame of the shutter (see figure 6).

The aperture of the shutter is designed to regulate the solar flux with a tolerance of 3%. In other words, it is possible to increase o reduce the solar flux in 3% step by step. The shutter is operated with a DC motor of 24 V. The aperture is measure with an encoder placed in the main axis of the elements of the shutter.

It should be noted that the instrumentation and control for the solar tracking of the heliostat and the instrumentation and control for opening and closing the shutter was made with the same architecture in *LabView*© previously developed for the solar furnace of CIE [6].

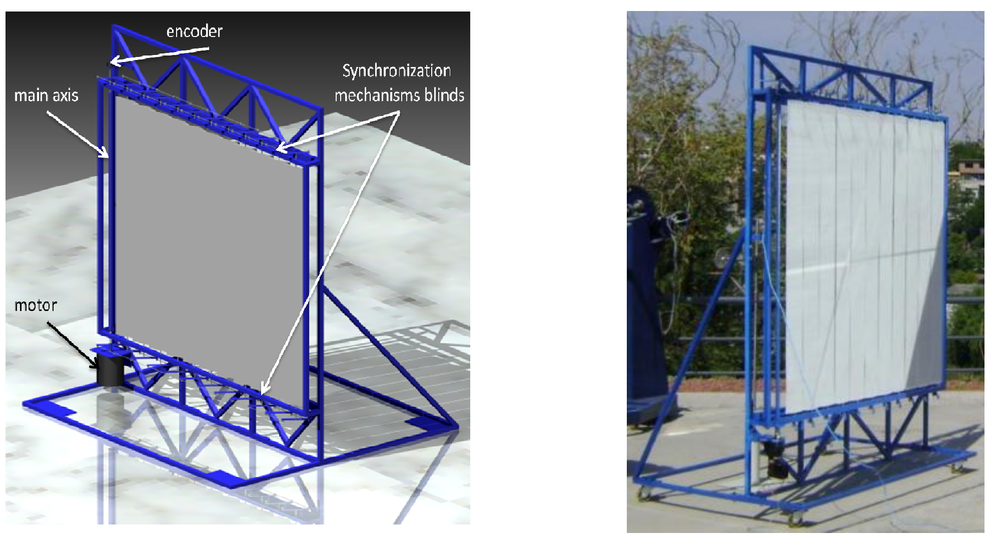

Fig 6: Scheme and Photograph of the MSF

4. Preliminary operation of the MSF

The heliostat, the shutter, and the concentrator were aligned in the north-south direction in order to operate the MSF. Based on the focal length of the DEFRAC 2.027 m, a pedestal with a height of 1.35 m was placed to hold the receiver. The pedestal was as slim as possible to minimize the shadow of this element. On the other hand, the shutter is placed at a distance of 2.9 m and the axis of rotation of the heliostato lies 2.6 m away of the shutter, as shown in Figure 6.

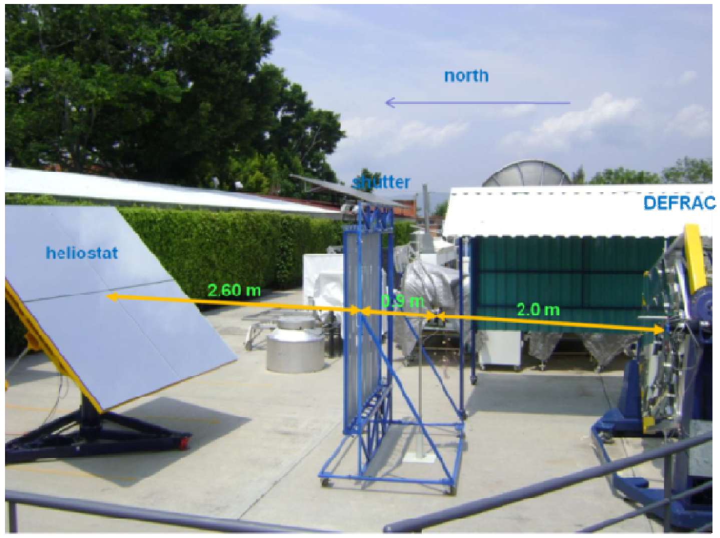

Fig 7: Operation of the MSF.

To study the performance of the MSF, an experimental campaign was conducted. The images formed in the receptor were captured by using a CCD camera that was placed in the focal axis system. The receiver is a target with a lambertian surface where the concentrated solar power arrives. Figure 8 shows three images of the distribution of the spot produced by each group of the mirrors of the concentrator: A, B and C.

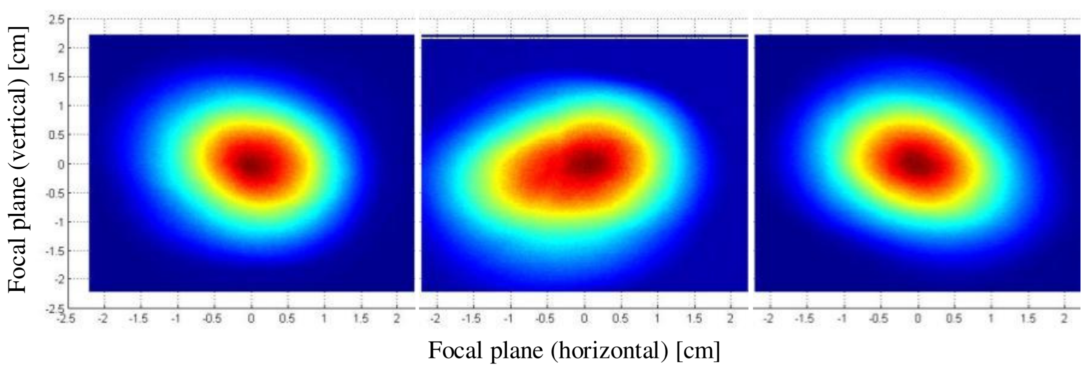

Fig 8: Relative solar flux from each group of mirrors from DEFRAC. (left) mirror from group A, (middle) mirror from group B, (right) mirror from group C

On basis of these images it was possible to simulate the concentrated solar flox that could be obtained from MSF. The overlapping of the images was performed by matching the peaks of each distribution in the same point, distributions were joined in a single mesh for combined irradiance profile for all mirrors. Figure 9 shows the theoretical distribution of radiation by superimposing three groups of mirrors. If it is compared the result obtained for the MSF with the previous results obtained experimentally for DEFRAC, the optical error introduced by the heliostat and alignment method can be estimated. Therefore the total beam width is $\sigma_{tot,MSF}$ 6.8 mmrad

$$\sigma_{tot,MSF} = \sqrt{\sigma_{sun}^2 + \sigma_{optical}^2 + \sigma_{heliostat}^2} \tag{4}$$

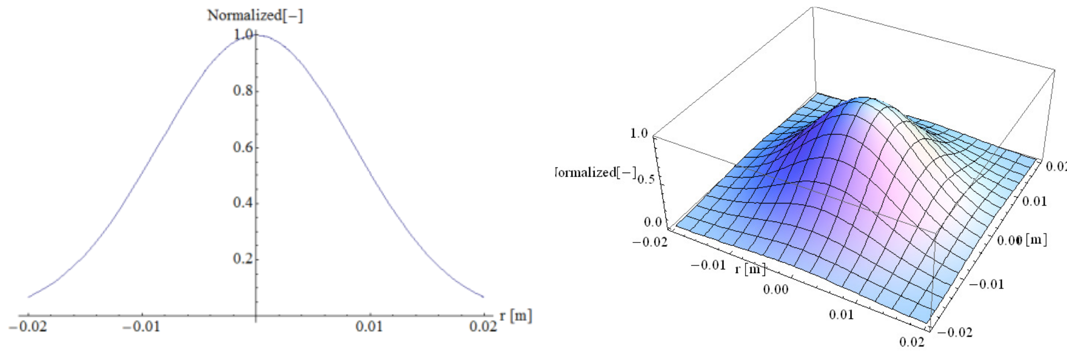

Fig 9: Theoretical distribution of the MSF

The energy distribution in the spot of the MSF, can be modelled by using equation (1) but it is necessary to take into account the reflectivity of the heliostat ρ_H:

$$G(r) = \pi f^2 \rho_r \rho_H G_b F_A (cos^2\varphi_r - cos^2\varphi_{min}) \frac{a \exp\left(-a\left(\frac{r}{R_{spot}}\right)^2\right)}{\pi R_{spot}^2 (1 - \exp(-a))} \tag{5}$$

where the parameter *a* is established in this case as

$$\boldsymbol{a} = \frac{R_{spot}^2}{2\left(\sigma_{sun}^2 + \sigma_{optical}^2 + \sigma_{heliostat}^2\right)} \tag{6}$$

The parameter *a* is obtained close to 2.5 during the operation of the MSF.

It is important to indicate that in the operation of the MSF the size of the spot is 2.65 cm in diameter with a mean concentration of 1350 suns, and a solar concentration peak close to 2400 suns. Note that the mean concentration and peak concentrations of DEFRAC were reduced when it is used as a MSF.

Based on the experimental images it is possible to adjust a normal distribution for the irradiance of the spot and it is possible to calculate the overall standard deviation that it is 6.8 mrad. This value include both the width the sunshape and the contribution of each optical error introduced by the heliostat and alignment method. In order evaluate the optical errors of the MSF it is necessary to carry out the deconvolution of the solar distribution of the spot. In a first approximation, a deconvolution was performed taking into account the profile of a standard sun, which corresponds to an average of observations carried out with the Lawrence Berkeley Laboratories circumsolar telescope at 11 sites throughout the United States (see for instance [7]). The results show that the optical error of the MSF is an approximately 3 mrad.

5. Conclusions

The DEFRAC was became with the construction of the two main components: the heliostat and the shutter. The heliostat was designed with a reflective surface of 5.6 m2, ensuring that the ray deviations, from the focal axis, were less than 1 mrad. Moreover, the dimensions of heliostat allowed, from mini solar furnace, an operation minimum of 4 hours, even in summer. The shutter design ensured a shade less than 1% of the area of concentrator. The results show that the optical error of the MSF is an approximately 3 mrad.

Acknowledgment

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