Simulation, Design and Construction of a Polar Parabolic Cylinder Collector (CCPP)

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Abstract: ***The objective of this work is to verify the efficiency of a polar parabolic cylindrical collector (CCPP). Latitude-oriented systems differ from traditional ones in that, in polar tracking, the axis of rotation of the collector is tilted to match the latitude of the site. The thermal transfer of these elements generates a linear focus through which a fluid circulates for the generation of electrical energy or process heat. For this, different softwares have been used; to simulate the incidence of the different angles of solar rays, we have considered the ZEMAX-EE, while the Rhinoceros 7 was used to design the geometric configuration and the collecting surfaces. The location chosen was the Optics, Calibration and Testing Laboratory of the Astronomical Observatory of La Plata, at 34º54'28" South Latitude, 57º55'54" West Longitude. Geo positioned by GPS by the Department of Surveying of the Faculty of Engineering-UNLP. The results obtained and contrasted with theoretical calculations present promising evidence for the construction of medium temperature solar fields.***

Keywords: Parabolic trough concentrator, process heat, solar energy, concentration ratio

1. Introduction

The Sun is a gigantic nuclear reactor that releases large amounts of energy in the form of light and heat that then reach the Earth's atmosphere. It should be borne in mind that the Earth is surrounded by the atmosphere, and this gives rise to different phenomena causing the energy captured at sea level to decrease. Throughout the terrestrial year, said energy does not reach our planet in a uniform way; it varies slightly, depending on the time of day, the seasonal inclination of the globe with respect to the Sun, and the different areas of the Earth's surface it hits.

Concentrated solar energy emerges as an option to harness solar power. This is used to a greater extent to generate electricity, as well as process heat. There are several line and point-focusing systems that concentrate solar power: Fresnel, parabolic dish Stirling engines, Heliostats with tower concentrator systems. This paper studies the latter — parabolic trough concentrator systems (PTC). [1] [2] [3]

When it comes to solar concentration, the orientation of the system is of utmost importance. The system must be oriented towards the Sun and dynamically track it. Otherwise, the concentration will be inefficient, causing the consequent energy loss of the whole set, and having a maximum peak at solar noon. Systems oriented according to latitude are different, since, in polar tracking, the axis of rotation of the collector is tilted so that it coincides with the latitude of the site.

For the characterization and design of the prototype, we have worked with the theoretical basis of an article, previously published by our laboratory [4], and to simulate the incidence of different angles of solar rays, the ZEMAX-EE 2005 software was used.

The geographical position of the chosen site was first considered, and, later, located in the Optics, Calibration and Testing Laboratory of the La Plata Astronomical Observatory, at 34º54'28” South Latitude, 57º55'54” West Longitude, in a North-South orientation. The equipment is designed with solar tracking on the axis, East / West.

In the present work, the methodological development and the calculation of the geometric parameters for the design and construction of a CCPP are exhibited. The simulations made with different softwares, the construction of a prototype, the results obtained and their analysis are presented in the following sections, later we arrive at the conclusions.

2. Methodology

Figure 1 exhibits the parameters that were taken into account for the present development: collector axis, parabolic trough concentrator, receiver, solar radiation, receiver diameter (D), maximum radius of the parabolic concentrator (r_r), edge angle (ϕr), aperture (Wa), angle between the axis of the collector and a beam reflected at the focus (ϕ) and mean acceptance angle (ϴm).

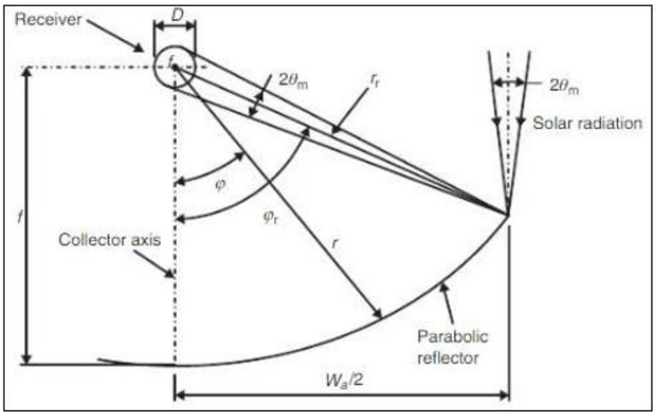

Figure 1: Cross-section of a parabolic trough collector with circular receiver. Kalogirou, 2009 pp.195

This study is designed and dimensioned for the installation of a small solar field for a prototype plant of 24 m^2 of collection area, arranged in four concentration modules of 6 m^2. These modules were built based on a structural synthesis of torque tube [5] with N/S orientation. Fig. 2 shows the orientation and latitude.

When setting out the site, a distance of 4.5 m will be established to minimize shading losses due to the relative position between rows of collectors.

Figure 2: Location and north/south orientation.

In fact, the magnitude of the rim angle determines the material required for the construction of the parabolic surface. The curve length of the reflective surface is given by:

$$S = \frac{Hp}{2} sec\left\{\frac{\phi r}{2}\right\} tan\left\{\frac{\phi r}{2}\right\} + \left(\left\{\frac{\phi r}{2}\right\} + tan\left\{\frac{\phi r}{2}\right\}\right) \quad (1)$$

where S is the length of the curve reflecting surface, ϕr is the angle of edge. In addition, *f* is the focal length.

$$f = \frac{Hp}{4} \quad (2)$$

The straight side (latus rectum) Hp of the parabola, that is, the opening of the parabola at the focal point of the reflecting surface is given by equation 1.

The opening is given by:

$$Wa = 4f tan\left\{\frac{\phi r}{2}\right\} \quad (3)$$

The system concentration ratio [6] is a strictly geometric dimensionless parameter, defined as the relationship between the opening area of the collector and the absorption or receptor area.
It is given by the equation:

$$RC = \frac{la}{\pi D} \quad (4)$$

Where *la* represents the parabolic trough concentrator width and D, the absorber tube outer diameter. Once the geometric parameters of the PCC were calculated and defined, the parable was designed with the Rhinoceros software as seen in Fig. 3

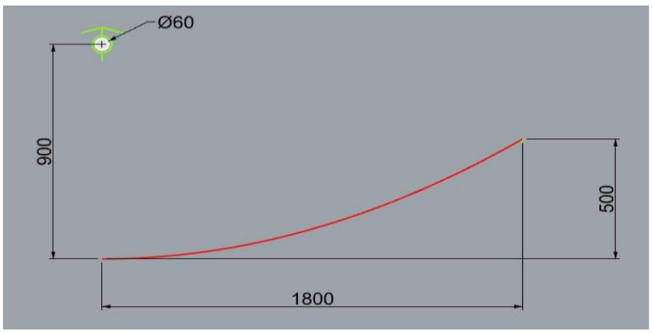

Figure 3: Geometric profile design

These values were given by the replacements in equation 3.
Wa = 1800mm

This was done taking into account the commercial presentation of float glass in Argentina, which is 2m. and the curve dimension *(S)* is 1800 mm.

3. Simulation parameters and Geometric Design

This Section describes the different geometric parameters taken into account when designing the device. We will also present the expected values for a device with the characteristics described and installed in the place already mentioned above.

3.1 Concentration ratio

If we replace in equation (4):

$RC = la/\pi D$
$RC = 19{,}148$
with: *la* = 3.6 m and D = 0.06 m

3.2 System focal ratio

This dimensionless parameter is defined by:

$$F = f/D\,1 \quad (5)$$

$F = 0.25$
with: *f* = 0.9 m and D1 = 3.6 m

where D1 is the diameter of the collector. In solar concentration applications with designs of paraboloid or spherical revolution optics, there is an acceptable value for the focal ratio between: 0.7 > F > 0.6. For parabolic trough systems (PTC), values between: 0.5 > F > 0.3 are used.

3.3 Solar incidence angle (θ)

To analyze the effect of θ on the thermal energy captured, it is first necessary to specify the collected portion (Cf). This is set by the relationship between the power received by the absorber (Pr) and the solar power (Ps) captured by the collector in real time.

$$Cf = \frac{Pr}{Ps} \qquad (6)$$

In the case of the chosen site, a solar radiation measurement system has been made, based on a field pyrheliometer detector with an error range of around 8%, on an equatorial mount, and solar tracking, which allowed detailing an average of Ps of:

Ps = 1100 W/m^2 (La Plata – FCAG)

After evaluating the reflectance, absorbance and transmittance losses in the PTC mirror system, the approximate value of Pr that is concentrated in the detector is averaged at:

Pr = 916 W/m^2

Then, substituting in equation (6) we get:

$$Cf = 0.832\ W/m^2$$

3.4 Geometric losses. Inherent collector losses

These types of losses cause the effective collecting area (Ae) of the collectors to decrease due to the angle of incidence ϕ. [7].

The values were calculated through (Eq. 7) and (Eq. 8).:

$$Ae = la.\, l\phi = la.\, fm.\, tan\phi \qquad (7)$$

$$fm = f + \frac{\frac{f}{la}}{48.f_2} \qquad (8)$$

Being la, the width of the parabolic trough concentrator; l, the parabolic trough concentrator length and f, the focal distance. Meanwhile fm represents the average distance between the surface of the parabola and the absorber within the same cross section of the collector, and ϕ, the angle of incidence Substituting into equation (8) with *f* = 0.9 m and *la* =3.6 m we obtain:

$$fm = 0{,}906m$$

Then, substituting in equation (7) with the above value of *fm* and taking tan 34.5° we get:

$$Ae = 0{,}560m^2$$

4. Ray tracing simulation

Here, we present the simulation of geometric formation of rays in a system of concave mirrors with ZEMAX-EE. For this work, the simulation between two concave surfaces was compared using the analytical data provided by the System concentration ratio (1), System focal ratio (2) and the Geometric parameters [7] as can be seen in Fig. 4

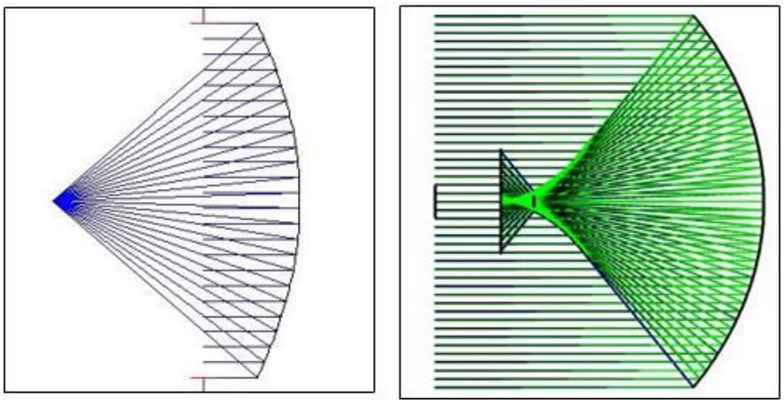

Figure 4: Left is a simulation with a parabolic mirror. right with a spherical one

On the left, a parabolic mirror is used where all the rays are concentrated in a focus at a certain focal length, while on the right, a spherical mirror is the chosen one. This means that it will generate focus, depending on the height of the incident rays, and when they are cut in the optical axis, a spherical focal zone called caustic is generated.

5. Final Design

In this section, the parameters for the final design of the device are laid out.

5.1 Geometric Parameters [7]

The choice of the geometric figure and *f* (the focal length of the system) are evaluated as the first parameters for dimensioning, as per Section 3. Parabolic curves and an *f* = 0.9 m, with a Focal Ratio system: F= 0.3 was used, because it reduced energy dispersion in the absorber. The focal line is well defined and without aberrations, adjusting to the concentration, intra or extra focal, in relation to the increasing or reducing energy. Fig. 5 illustrates a 3D modeling with the Rhinoceros 7 software to generate the geometric configuration (left) and verification of the definition of the concentration focal line at the nominal focus (right).

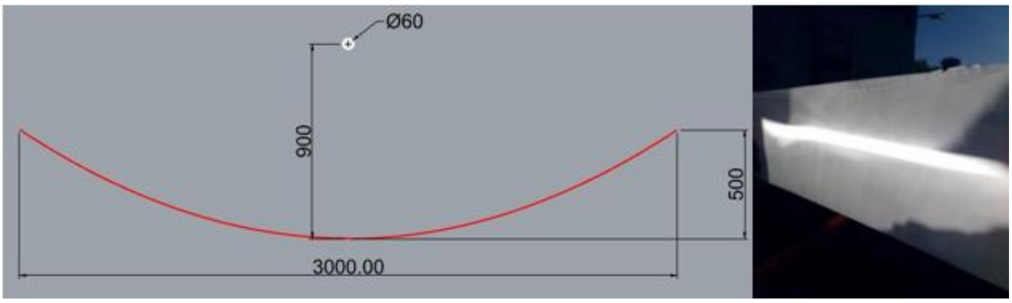

Figure 5: Final geometric design made with rhinoceros 7 software with the parameters of a parabolic collector.

5.2 Collecting surface

The collecting area (parabolic mirror) covers 6 m^2 (2 m long x 3 m wide). A 4 mm float glass from Argentinian industry, mirrored on the second surface was implemented for this project. This is a flat, transparent, distortion-free crystal that has flat, parallel faces with bright, fire-polished surfaces that are perfectly transparent. As can be seen in Fig. 6, to make the construction of the prototype feasible, the arrow (f) of the obtained curve, which represents the distance from the center of the bow to the center of the chord, is analyzed and reconfigured into two new parabolic curves whose total result is the same. However, they individually have a smaller and different (f), eight of them being f= 0.03398 m and, the rest, f= 0.02496 m, adding a total of 16 surfaces for the complete collector

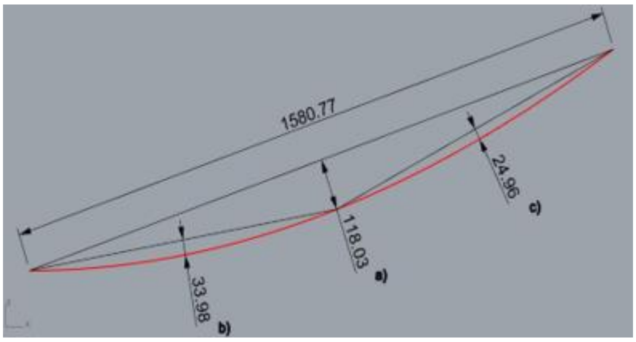

Figure 6: a) f=118.3 cm (entire surface), b) f =33.98 cm (surface 1), c) f =24.96 cm (surface 2).

5.3 Results

Using the previous equations, the final parameters of the prototype were determined.

	S (mm)	*f (m)*	*Wa (mm)*	*RC*	*F*	*Cf (W/m^2)*	*Ae (m^2)*	*fm (m)*	*lat. (°)*
Nominal	1978.96	0,9	1800	19,148	0.25	0.832	0,56	0,906	35
Prototype	1661.89	0,9	1500	15.95	0.3	0.832	0,685	1,108	34,4

T 1. Comparative table of geometric parameters

6. Discussion

After comparing the calculated results with the real ones, we can observe that:

The length of the curve reflecting surface *(S)* represents a loss of 16.02 %, On the other hand, *RC* represents a loss of **3.19** units with respect to the theoretical values. *F* shows us that the prototype is within the tolerance range mentioned in section 3b. The positioning with the latitude of the place presents an error of **1.714%.** Finally, *Ae, represents an increase in loss of collection area* **22%** compared to what was calculated in section 3d.

Of this last result, we observe how the displacement factor of the losses inherent to the collector is represented. As shown in Fig. 7., taken in December and March 2021, a displacement (*D*)of 37.8 cm towards the North direction (left) is observed, confirming how these losses vary throughout the year.

Figure 7: Displacement of rays.

In addition, a comparison was made with thermographic instruments (Testo 785 thermal imaging camera) to determine temperature variation along with concentration plane, and to detect collimation defects, as shown in Fig. 8.

This figure shows records of variations thermal checks, marked as M1 and M2 (left), and the thermal check of the entire system (right).

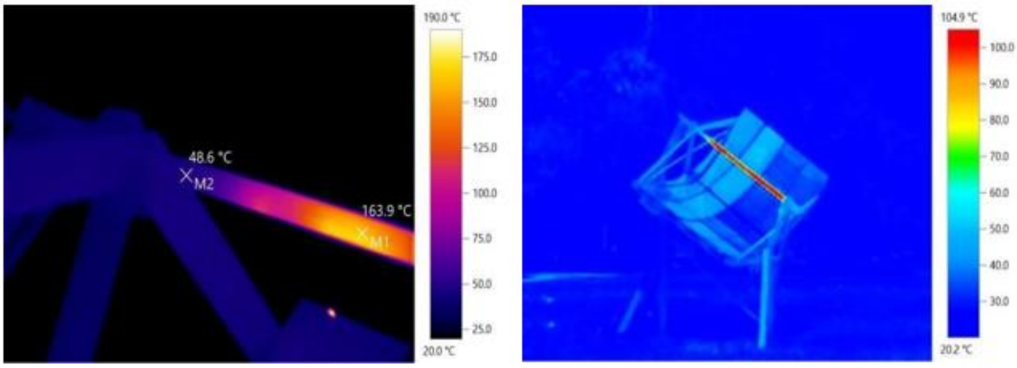

Figure 8: Measurement with thermographic camera

7. Conclusions

After the characterization and construction of a Polar Parabolic Cylinder Collector (CCPP), it can be verified that, despite the differences obtained between the calculator values and the real ones recorded with the prototype, the results obtained are within an acceptable tolerance range.

These systems present a more stable behavior throughout the year since polar tracking shows less variation in the angle of incidence.

To compensate for the geometric losses inherent to the collector, the displacement factor must be taken into account since this type of loss causes the effective collector area (Ae) to increase due to the angle of incidence ϕ. To do this, we will have to lengthen the absorber tube 40 cm in the north direction and 40 cm in the south direction to make the most of all the concentration rays in the different seasons of the year. In this sense, if more than one concentrator is installed, a shadow study must also be carried out to rethink and avoid geometric losses due to the position between the rows of collectors.

It has been proven that correct collimation of reflective surfaces allows increasing the definition of the focal line and with it, its intensity. To do this, the support structure of the reflective optical parts must have X (height) correction systems that allow the linear focus to be adjusted on the absorber tube.

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Disclosures
The author declares no conflicts of interest.

Data availability statement policy.
Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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