Theoretical analysis of a polar parabolic trough collector behavior in a subtropical region

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Abstract

The performance of a solar radiation concentrating system to be applied to direct steam generation is reported. Such system consists of an ensemble of a trough collector and a receiver, through which water flows as heating fluid. The trough collector is inclined according to the latitude coordinate, parabolically curved and one-axis tracked. The assembly is analyzed via computer tools based on Tonatiuh Ray-Tracing methodology. The computer analysis allows distinguishing the Polar parabolic trough collector from the classic parabolic trough collector. Due to a reduction in the cosine effect in the Polar parabolic trough collector, there is a significant improvement in the cosine optical efficiency throughout the year, especially in the winter season. The polar parabolic trough collector is a promising collector for concentrated solar power systems at subtropical latitudes, it provides a better usage of the solar resource for the processes involved in getting heat or generating electricity, especially in medium and low scale applications.

Keywords: Concentrating Solar Power, Parabolic Trough, Direct Steam Generation

1. Introduction

The demand for energy is constantly growing at the global level. Predictions indicate that between 2015 and 2040 the world energy consumption will increase by 28% (Energy Agency, 2017). The economic development achievement from the last century as a consequence of the easy access to oil, coal and natural gas, whose oxidation processes have contributed to the increase of the environmental pollution and also to a dangerous global warming.

Solar energy is one of the forms of alternative energy with the potential to supply the heat and power demanded by all the Earth's population. To get electricity from solar energy, it is possible to take advantage of either of the photovoltaic effect or the Sun's rays heat content (Michaelides, 2012; Höök and Tang, 2013). The latter is achieved by transforming the solar radiation into heat with the help of solar mirror collectors to intercept the sunlight and reflect

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it onto a receiver. It is essential for the collector to follow the Sun in its apparent movement; otherwise, the Sun’s rays cannot be properly concentrated on the receiver, and part of the potentially collected energy would be lost. Having this in mind, well-developed systems to concentrate sunlight have been proposed (Lovegrove and Stein, 2012). Among these, the parabolic dish and solar tower systems concentrate sunlight onto nearly a point, whereas Fresnel linear and parabolic trough collectors systems focus and concentrate sunlight onto nearly a line.

Parabolic trough collectors (PTCs) intercept solar radiation and, after its reflection, concentrate it onto a tubular receiver located at the focus line Figure 1.; inside the receiver, a heat transfer fluid (either thermal oil or water) is heated by the solar radiation. Concerning direct steam generation (DSG) the fluid is water, it is directly converted into steam, which is obtained either saturated or overheated, this last overheated steam is used directly in a Rankine cycle to get electricity. The whole assemblage, collector and receiver, is mounted on a frame that tracks the solar path in the north-south axis during the diurnal movement.

Because PTC follows the Sun on a single axis, the most suitable location for PTC is the equator, since here the Sun is closer to the zenith during the whole year, and the Sun’s rays enter perpendicularly to the aperture plane of the collector the longest. The perpendicular entrance of the Sun’s rays does not occur in subtropical regions. Because the Sun never crosses the zenith in its apparent daily movement; PTC efficiency is lower in subtropical regions (El-Kassaby, 1994),

Several configurations for the PTCs have been proposed and studied either experimentally or by computer simulation (Kumar, Chand and Umrao, 2013; Marif *et al.*, 2014) among them, there is the polar configuration (PPTC), where the collector is inclined according to the latitude to overcome the latitude difficulties. For PPTC, the movement of the system is performed on a single inclined axis, and it is always parallel to the rotation axis of the Earth.

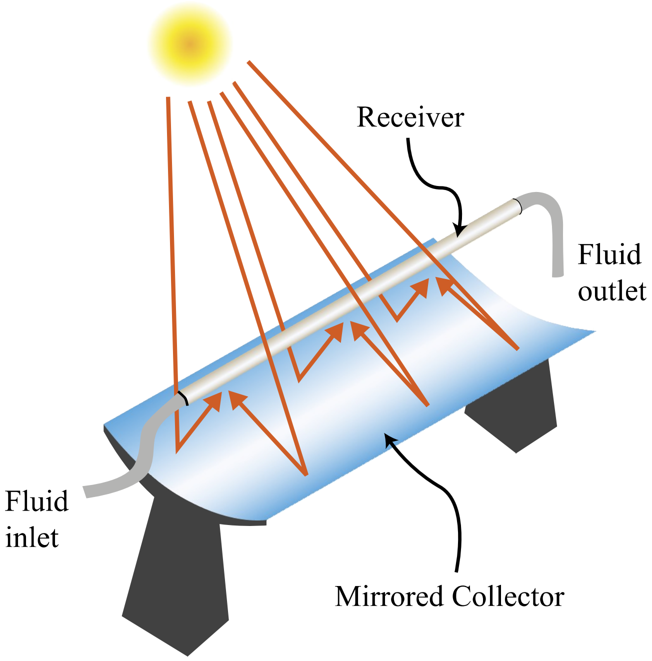

Figure 1 : Scheme of a classic PTC device

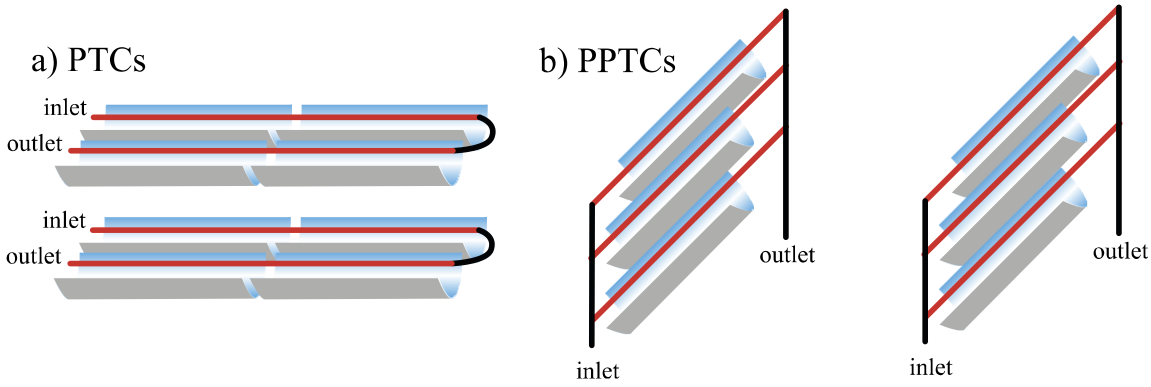

Figure 2: Schemes of an ensemble (a) classic PTCs and (b) PPTCs

Figure 2a shows a typical configuration for PTCs, where a number of them are arranged in series, forming a unit called loop. To apply the concentrated solar technology to a small solar field in a subtropical region, it is proposed to use shorter PPTC. They are assembled in a parallel arrangement, as shown in Figure 2b.

The PPTC choice is made to tackle two problems encountered in the direct steam generation using PTCs. The first one is that, due to the variability of the incidence angle (θ) defined between the normal to the trough aperture plane and the solar position, there exists a cosine effect, which causes a loss in the energy flow collected; and the second one is the generation of a biphasic flow water/steam in the receiver, after water evaporates generating that in the hours far away from midday, when the reflected radiation hits the receiver laterally, a poor heat exchange between the walls of the hot receiver and the steam occurs (Zarza Moya, 2003), as it is shown in Figure 3. Regardless of the presumption that the inclination of the system will greatly help to diminish the biphasic flow, this change of behavior of the heat transfer fluid within the receiver will not be discussed in this paper, although it is proposed for further research.

As the climatic condition varies significantly from one year to another, trustful results cannot be obtained by using parameters measured in just one single calendar year. It is more appropriate to apply the statistical year, made of 12 typical meteorological months, based on the field measurement ranging over decades. The year then is defined as the typical meteorological year (TMY). Studies about the behavior of PPTCs with data provided by using TMY are yet lacking.

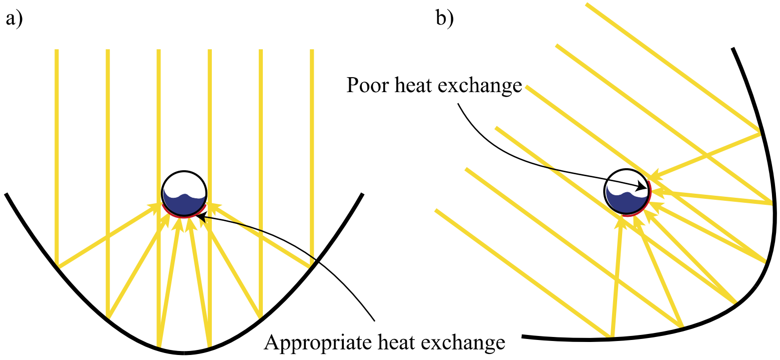

Figure 3: Heat exchange in PTC: a) at noon, b) in the morning/afternoon

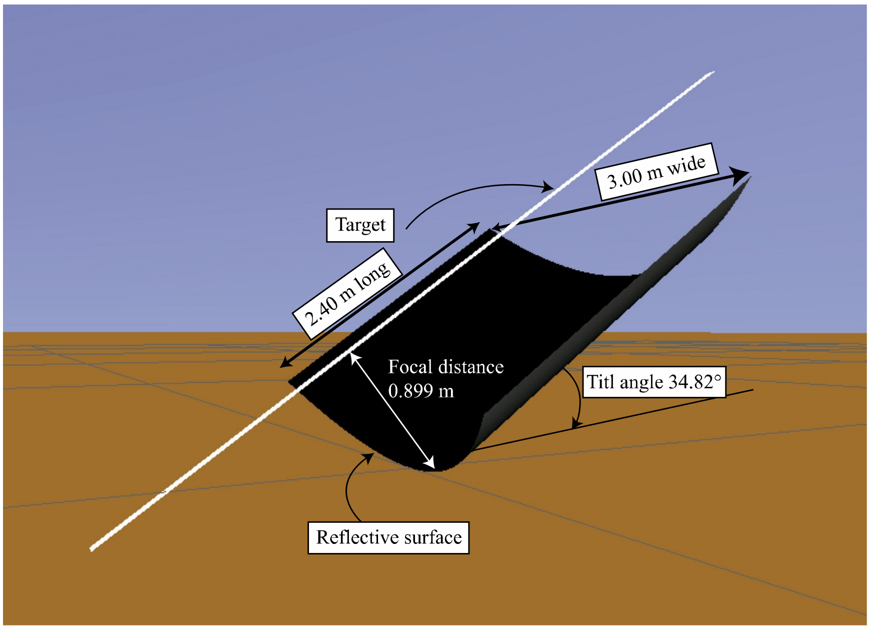

Figure 4: Model used in the simulation (with some indications as reference)

The present work analyzes a PPTC for DSG which will be placed at Ezeiza Airport, Buenos Aires (34.82° south latitude). The analysis will be performed through computer simulation in a TMY, and the results will be compared to those of a conventional PTC.

2. Methodology

The Tonatiuh Ray-trace software is used for the computer optical simulation of the system; it employs the Monte Carlo method to model the path of a large set of particles that represent photons emitted by sunlight (Blanco, Amieva and Mancillas, 2005).The software needs to know the dimensions of the collector and its spatial orientation, so the size of the collector is fixed at 2.40 m long and 3.00 m wide and the focal line is set at 0.889 m measured from the parabola vertex as shown in Figure 4. The reflectivity of the surface is set as 0.85, and the σ_{slope} is fixed as 3 mrad, in accordance with an average real mirror (Krüger *et al.*, 2008; Xu *et al.*, 2015; Giglio *et al.*, 2017).

For the modeling, a target is located at the focal zone of the collector. The target is symbolized as a rectangular plate 4.00m long and 0.20m wide centered with the collector, and it follows the focal strip with its longer side.

The target is used to analyze the optical image of the reflected photons. An amount of 5x107 modeling photons in a pillbox distribution is chosen. The photons impact and reflect on the collector mirror surface, and finally impact the target, Figure 4. With the coordinate values of each photon collision, the software generates a binary data file. The raw data were processed by using different algorithms programmed in Matlab. Therefore, to measure the local concentration of hitting photons, a 1000x1000 rectangle mesh is built on the target. The mesh is used to count the number of photons impacting each cell. The data are filtered excluding the diffuse zones, considering only the area of highest luminous intensity, which contains 88,5 % of the impacted photons.

To analyze the behavior of the collector for the location 34.82° south latitude (Ezeiza

Airport), three solar positions were selected to represent the maximum and minimum incident angle θ, i) the summer solstice, θ= 22.41°, ii) the equinoxes of spring and autumn θ = 0°, and iii) the winter solstice θ;= -22.41°. The θ values are considered constant during the selected days, as its variation is negligible according to the Sun positions calculated in the present work.

To study the effect of θ on the collector performance it is necessary to define a parameter named the collected fraction (F_c) which is the relationship between the power per collector area delivered to the receiver (collector radiation, R_c) a and the power per unit area provided by the Sun at the location (solar radiation, R_s):

$$F_c=\frac{R_c}{R_s} \tag{1}$$

F_c value is 1 when the system is perfectly aligned (θ = 0), and all incident rays hit the receiver (ideal mirror). When θ ≠ 0, F_c decreases and so does R_c according to:

$$R_c=\eta_{coso}R_s \tag{2}$$

where η_{coso} is defined as the cosine optical efficiency:

$$\eta_{coso}=\cos(\theta) \tag{3}$$

For both PPTC and PTC systems, θ can be calculated at any time using the solar position vector $\vec{U}$obtained by using the Solar Positioning (Reda and Andreas, 2004) represented as:

$$\vec{U}=(ux,uy,uz) \tag{4}$$

To determine the θ value, another unitary vector $\vec{n}$, s defined, parallel to the rotation axis of the collector.
For PTC, the $\vec{n}$ vector is:

$$\overrightarrow{n_{PTC}}=(1,0,0) \tag{5}$$

as its rotation axis is aligned with the local meridian and placed horizontally, while for PPTC the vector is:

$$\overrightarrow{n_{PPTC}}=(\cos(\beta),\sin(\beta),0) \tag{6}$$

where β is the inclined angle of the collector. Consequently:

$$\theta=\arcsin(\vec{n}\cdot\vec{U}) \tag{7}$$

To calculate θ by using the Solar Positioning Algorithm, the time interval was selected as one hour for the whole year. In the algorithm, in addition to the positioning data (latitude, longitude, and altitude), the values of humidity, atmospheric pressure, and temperature of the typical meteorological year TMY at Ezeiza Airport were introduced (Bre and Fachinotti, 2016).

3. Result and Discussion

For PPTC, during the solstices, the daily variation of θ was 0.23º and during the equinoxes 0.38º (the average variation for each day throughout the year was 0.34º). These values are quite constant for θ throughout the day, compared to the results obtained for PTC with average daily θ variations of 34.57º. In Figure 5, the variation of θ for PTC and PPTC during all year hours is shown. To make the chart more understandable, insets corresponding to the solstices and the autumn and spring equinoxes are shown.

Figure 6 shows the variation of η_{coso} for each θ during all year hours, together with the inset corresponding to solstices and the autumn and spring equinoxes, and Figure 7 shows the monthly average θ daily variation along a typical year.

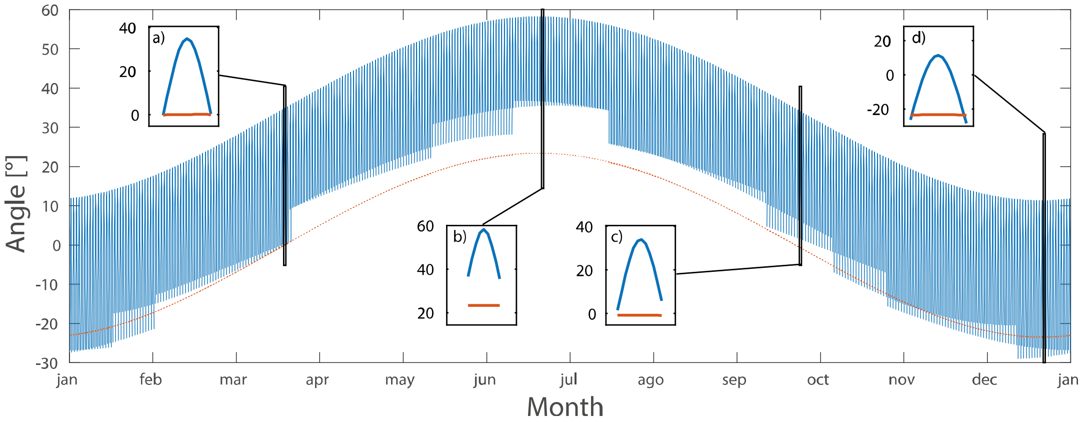

Figure 5: Variation of θ throughout the year. In blue for PTC and orange for PPTC. Insets show the magnification of one day in the chart at a) autumn equinox, b) winter solstice, c) spring equinox and d) summer solstice.

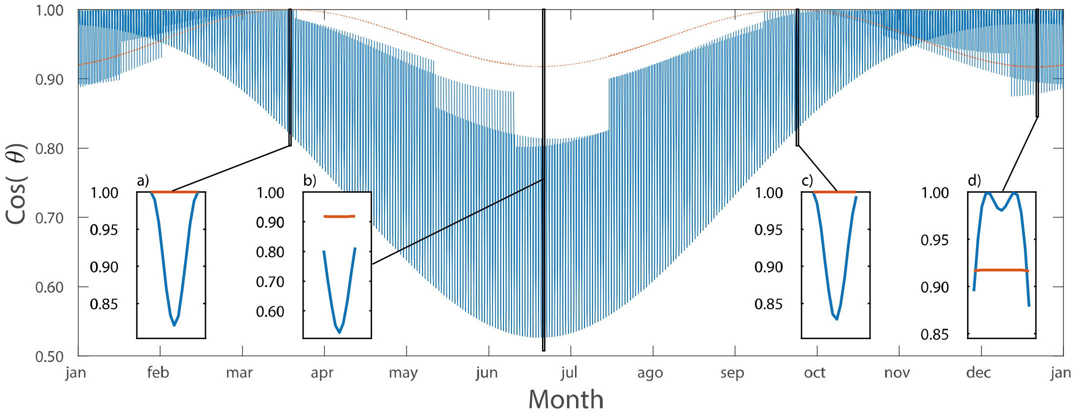

Figure 6: Variation of cos(θ) throughout the year. In blue for PTC and orange for PPTC. Insets show the variation at a)autumn equinox, b) winter solstice, c) spring equinox and d) summer solstice.

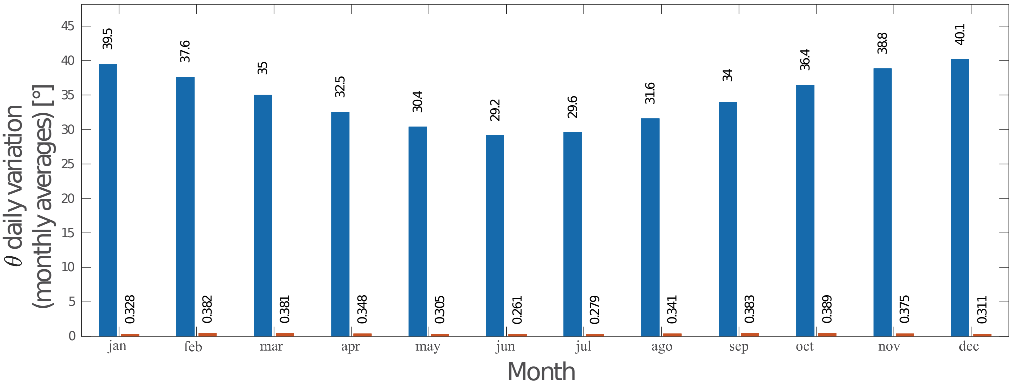

Figure 7: Monthly averaged θ daily variation along a typical year. In blue for PTC orange for PPTC.

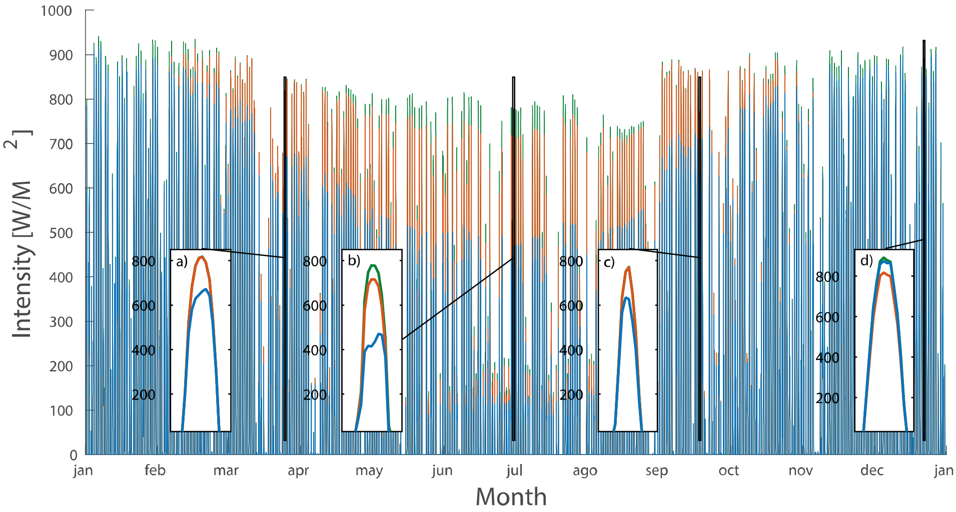

Figure 8: Variation of R_s (in green) and R_c (in orange for PPTC, in blue for PTC) throughout the year. Insets show the variation at a) autumn equinox, b) winter solstice, c) spring equinox and d) summer solstice.

To analyze the effect of η_{coso} on R_c , the other efficiencies are assumed equal to 1, and the typical meteorological year for Ezeiza National Airport is used, employing the data of direct solar radiation for R_s. Applying Eqn. 2, R_c can be calculated for both systems, Figure 8.

When a trapezoidal integration is performed for R_c values along the year, the amount of energy obtained for PPTC is 1.40 MWh/m^2 and for PTC 1.28 MWh/m^2. The relationship of these values with the trapezoidal integration of the R_s data (1.47 MWh/m^2) allows determining the annual efficiency for both systems due to the cosine effect, it being 0.96 for PPTC and 0.87 for PTC. It is also observed that, in addition to the increase in efficiency, the PPTC system shows that the energy collection is almost stable throughout the year and days. For PTC, large variations of collected energy, both daily and seasonal are observed, with a marked decrease in yield during the winter, Figure 8.

In all parabolic trough collectors, there is also a decrease in efficiency due to the so-called loss at the end of the collector, which occurs when the incident radiation at the end of the mirror is reflected off the receiver, Figure 9. The arrangement of PTC systems in series means that the loss at the end of the collector is small concerning the collection area; however, for PPTC due to its shorter length, the loss is significant.

After analyzing the focal areas at specified times, and applying the Monte Carlo methodology, the following results are obtained. i) at the summer solstice: the focal image extends 0.40 m below the collector, see Figure 10a; ii) at equinoxes: the focal image extends from the beginning to the end of the collector, see Figure 10b; iii) at the winter solstice: the focal image extends 0.40 m above the collector, see Figure 10c. The above Figures, justify why a modified receiver is proposed.

In order to determine the receiver dimensions, not only the length but also the width of the focal area is necessary to be considered. A width of 0.051 m for the equinoxes and one of 0.052 m for solstices have been obtained. Therefore, the receiver proposed has a diameter of 0.052 m and a length of 3.2 mm exceeding 0.40 m above and below the collector.

Base on the same analysis for a PTC with a length of 2.4 m, the calculated diameter of the receiver is 0.062 m. It is observed that the receiver area in PPTC is 10.6 % larger than in

PTC. Thermal insulation at the end of the receiver not in use is proposed to attenuate possible thermal lose (i.e. the bottom end from the spring equinox to the autumn equinox; and the top end from the autumn equinox to the spring equinox).

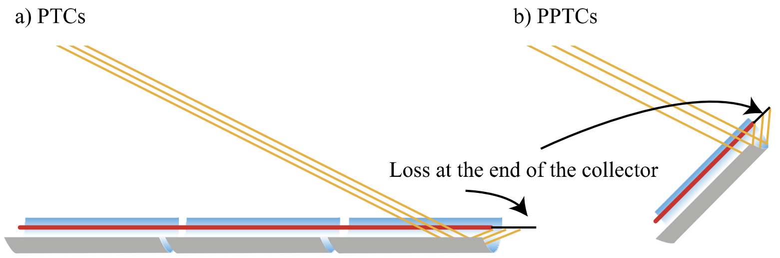

Figure 9: Losses at the end of the collector (a) PTC and (b) PPTC.

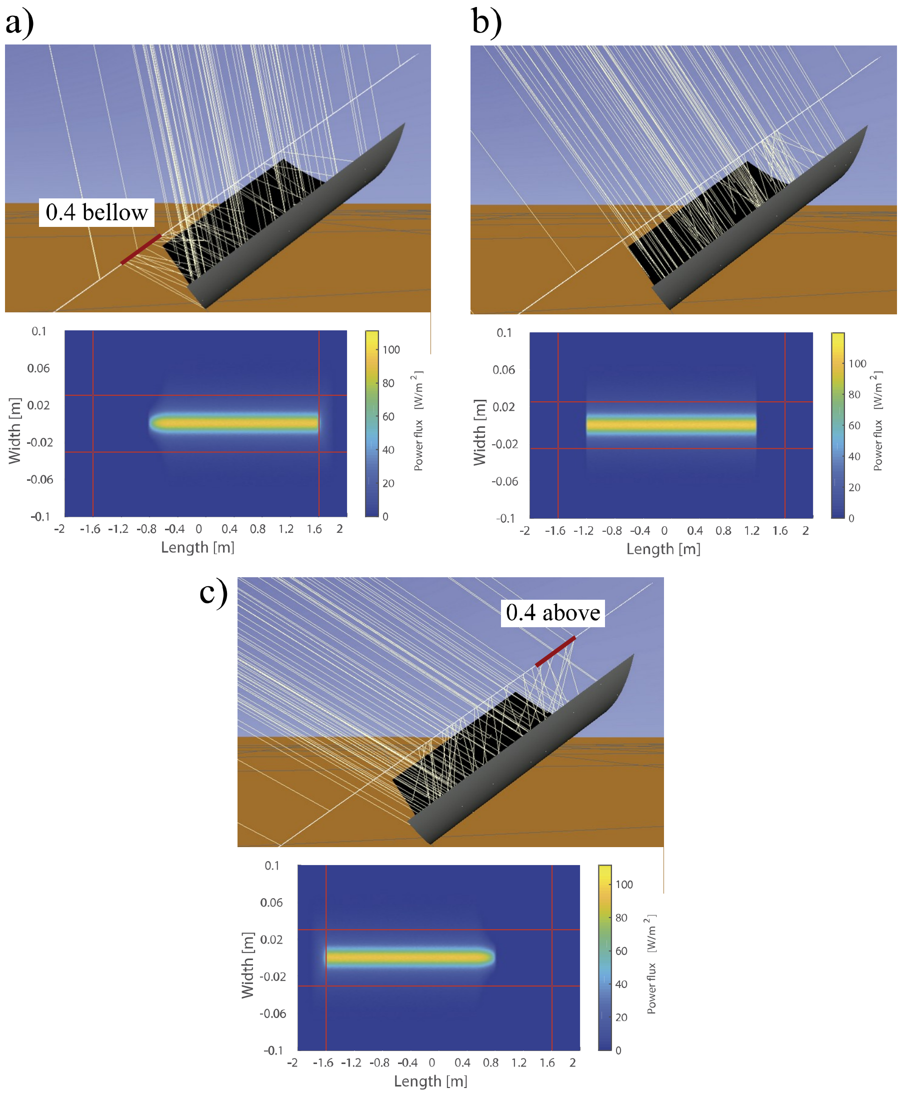

Figure 10: Ray tracing at different times of the year for PPTC. The onset and end of the proposed receiver are shown in vertical red lines, the width of the focal strip with 88.5% of the reflected energy is shown in the horizontal red line. a) at summer solstice b) at winter solstice c) at equinoxes.

Conclusions

The theoretical analysis allows distinguishing PPTC from the classic PTC solar collector. The

PPTC system has two important improvements to highlight. The first one is the reduction of the cosine effect, which shows an improvement of the collected fraction, $F_{c,}$ (from 0.87 in PTC to 0.96 in PPTC) throughout the year at the studied latitude. The second achievement is that there is a significant improvement in daily variations of the incidence angle for PPTC, increasing the stability of the system. Both improvements depend on latitude: The further from the equator, the more important is the difference between efficiencies.

Although the area of the receiver is 10.6 % larger than that corresponding to traditional PTCs, seasonal thermal insulation in the receiver can be used to reduce the thermal losses.

The use of PPTC systems is promising for their application at subtropical latitudes and provides a better use of the solar resource, especially in medium and small-scale applications, for the processes involved in obtaining heat or generating electricity.

5. Acknowledgments

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