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Performance evaluation of a parabolic cylinder collector applying the Monte Carlo ray tracing method

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Abstract

The purpose of this article is to evaluate the performance of a prototype parabolic trough collector for three proposed scenarios, where geometric designs with optical characteristics are tested according to the appropriate technological paradigm; low cost of maintenance and implementation, intensive local labor, materials and resources of the implementation area. The device was developed by the Energy, Automation and Control Systems Research Group GISEAC of the Unidades Tecnológicas de Santander for low-cost water heating; using materials and labor for its fabrication easily available locally. Monte Carlo ray tracing methodology was applied using the open-access software SolTrace and Tonatiuh. To select the geometric scenario to be simulated, the edge angle and the width of the primary reflection system of the device were varied. The results obtained showed that the aperture of the parabola has a direct impact on the drop in the concentration ratio (CR) percentage value and the performance of the prototype.

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Keywords: Monte-Carlo ray tracing, Performance, Soltrace, Solar concentrator, Tonatiuh

1. Introduction

Solar energy is present at higher levels than other renewable energies in the world [1], which makes it an alternative source for the production of electrical and thermal energy [2], through the different existing technologies [3]. For the production of thermal energy, solar thermal systems stand out from photovoltaic systems due to their capacity to reach operating temperatures above 1000°C [4]. Solar thermal systems can be technologically classified into three systems [5]; (i) low-temperature (1D) systems that reach up to 100 °C, (ii) medium-temperature (2D) systems that reach temperatures up to 300 °C [6], and (iii) high temperature (3D) systems with temperatures around 1000 °C. In the last decade, 2D and 3D systems have been referred to as Concentrating Solar Power (CSP) systems and have gained significant relevance due to their high participation in centralized systems around the world [7].

2D CSPs operate on the principle of linear solar concentration and are divided into two technologies [8]; (i) parabolic trough collectors (PTC) and (ii) linear Fresnel collectors (LFC) [9], [10]. On the other hand, 3D CSPs

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operate on the point concentration principle and are divided into two technologies [11]; (i) dish-striling and (ii) concentrating tower. The CCPs have single-axis solar tracking systems [12], [13], which ensure year-round utilization of the DNI [14]. The operation of the system is simple, the heat from the DNI is concentrated and transfers to a heat transfer fluid that is fed into a thermodynamic cycle to produce useful energy [15].

Currently, parabolic trough collector (PTC) technology stands out among CSPs for having the largest number of power generation plants installed worldwide [16]. The PTC system is composed of a primary reflection area, generally constructed with high reflectance mirrors that direct the direct normal radiation (DNI) to a secondary concentration system or linear focal point [17]. PTC is commercially the most widely available CSP technology worldwide [18] and its cost per square meter is around €300 for centralized applications, being very expensive despite its commercial maturity [19] [20].

In this context, different investigations have been developed in the last decade to reduce the implementation costs of PTC systems [21], based on the application of different materials, heat transfer fluids [22], and reflection area sizes [23]. However, these studies show low energy efficiencies derived from the search for reduced manufacturing, implementation, and maintenance costs. Generally, these technological developments have been applied in isolated and impoverished areas with a high presence of DNI as an alternative for hot water production [6] [24]. In addition, these developments are accompanied by performance analysis of the devices, applying methods such as analytical numerical simulation, experimental numerical simulation [25], CFD simulation [26], and the Monte Carlo ray tracing method (MTCR) [27].

Among the various methods of simulation and analysis of the behavior of the existent CPS [28], the MTCR method stands out for its simplicity and high accuracy of application, generating high-precision optical and thermal analysis, which allows predicting the behavior of the device under different conditions of DNI [29]. In addition, it has open-access software that facilitates the research process of this type of technology [27]. Eventually, the Energy and Automation Systems Research Group (GISEAC) of the Santander Technological Units (UTS) developed a PTC under the appropriate technology paradigm, i.e., a system developed with intensive local labor, local materials, low implementation cost, and easy maintenance. The device was evaluated experimentally presenting low efficiencies when compared to commercial systems, however, the purpose of the device was to heat water and use low-cost materials for its production.

Based on this, the objective of this work is to evaluate the performance of the PTC prototype developed by the GISEAC research group. To achieve this objective, the Monte Carlo ray tracing (MTCR) method is applied using Soltrace and Tonatiuh software to evaluate a series of previously selected scenarios. Accordingly, this paper is divided into 4 Sections. Section 1 describes the background of the topic to be addressed. Section 2 presents the methods and materials used. Section 3 presents the most relevant results and their discussion. Finally, Section 4 presents the most relevant conclusions of the work.

2. Method

2.1. PTC Prototype

The PTC prototype was built by the GISEAC research group and implemented at the Santander Technological Units in Bucaramanga, Colombia. The PTC was designed with the objective of heating water with higher flow rates than conventional solar collectors. The implemented prototype is based on three main components:

i. Primary reflector
ii. Receiver tube
iii. Solar tracking system

Additionally, the PTC prototype used two auxiliary systems for the execution phase: (i) a pumping system and (ii) a solar tracking system (Figure 1).

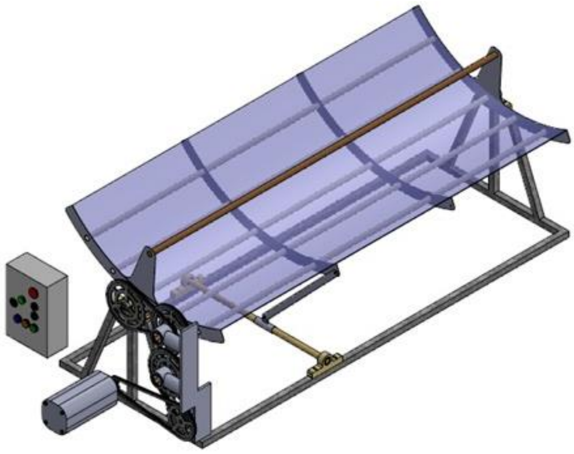


Figure 1. PTC prototype

The dimensions of the PTC prototype are presented in Table 1. The material of construction of the reflection system is stainless steel (AISI 430), 22 gauge with mirror polished finish.

Table 1. Dimensions of the components of the PTC prototype

Characteristics	Dimension	Unit
Collector opening area (W_c)	0.935	m^2
Opening width	550.08	mm
Collector length (L_c)	1700	mm
Edge angle (O_b)	90	degrees
Focal length (F)	164.48	mm
Receiver length (L_r)	1750	mm
Outer diameter ($D_{A,ext}$)	15.87	mm
Inner diameter ($D_{A,int}$)	13.85	mm
Receiver area (W_r)	0.04985	m^2

Finally, the optical characteristics of the components are listed in Table 2. The optical characteristics are fundamental for the development of the optical model simulated in the SolTrace and Tonatiuh tools. It is important to mention that the receiver tube has a black paint coating to improve the emissivity and absorptivity coefficients.

Table 2. Optical characteristics of the reflection system of the PTC prototype

Characteristics	Percentage
Reflectance (Reflector)	0.85
Emissivity (Receiver)	0.98
Absorptivity (Receiver)	0.98

2.2. Methodology

To analyze the optical and thermal performance of the PTC prototype, very accurate mathematical equations based on predictions are needed to study the optical coefficients. The determination of the performance of the PTC systems is mainly affected by four factors: (i) errors in the reflection area, (ii) angle of incidence, (iii) shading losses, and (iv) concentration coefficient. If optical models are applied, these types of impairments can be estimated to determine the actual system performance if the direct normal irradiance (DNI) to which the device is exposed, the geometry of the technology used, and the optical characteristics of the technology materials are known.

In this regard, the objective of this paper is to estimate the performance of a PTC prototype built by the GISEAC research group and three scenarios proposed as an improvement alternative. This performance evaluation, linking the dimensions of the real PTC system and the three proposed scenarios, will be analyzed by applying the open-access software SolTrace and Tonatiuh, whose application is widely recognized worldwide.

- Soltrace (https://www.nrel.gov/csp/soltrace-download.html) is a tool based on the Monte Carlo ray tracing method, developed in C++ code. It requires the use of a plugin called Google Sketchup, to develop a 3D design of the prototype to be analyzed, to directly feed SolTrace.
- Tonatiuh (https://iat-cener.github.io/tonatiuh/) is a tool based on the Monte Carlo Ray Tracing method, developed in C++ code. It requires the use of a code in Mathematica software for post-processing of the output data.

The simulation process in Soltrace and Tonatiuh involves the adaptation of the geometric model of the PTC to be evaluated. In turn, the DNI in W/m2 corresponding to the prototyping implementation site must be provided, as well as the number of sun rays. In previous works, Tarazona-Romero et al. [12] developed a study to determine the performance of a prototype CFL collector at the Technological Units of Santander. The authors carried out a previous traditional study and indicated that the average DNI in the area is 600 W/m2. Additionally, they corroborate the Soltrace and Tonatiuh manufacturer's version stating that the higher the number of simulation rays, the lower the error percentage of the results. In this context, a DNI of 600 W/m2 and several rays of 5,000,000 are used for the simulation process in the two softwares.

Additionally, mathematical expressions are required to determine the performance of the handcrafted PTC prototype from the flux intensities delivered by the simulation process in SolTrace and Tonatiuh. Equation 1 is applied for this purpose:

$$n_{spp} \ = \ n_{sf} * n_{rec} * n_{pb} \qquad (1)$$

Where n_{spp} is the performance of the PTC prototype, n_{sf} is the reflective area performance, n_{rec} is the receiver performance and n_{pb} is the power block performance. Also, the variation of the PTC system efficiency is determined from the optical efficiency of the reflection area (see Equation 2). The receiver throughput and energy block remain constant for the analysis.

$$n_{sf} \ = \ \frac{Q * \ A_{rec}}{DNI * \ A_{sf}} \qquad (2)$$

Where Q is the average flux generated by the reflection area, A_{rec} is the receiving tube area, A_{sf} is the area of reflection and DNI is the direct normal radiation. Finally, to determine the concentration ratio (CR), equation 3 is applied:

$$\mathrm{n}_{sf} = \frac{\text{Number of rays concentrated on receiver}}{\text{Total number of rays concentrated in the area reflection}} \qquad (3)$$

2.3. Simulation scenarios

Figure 2 shows the curves corresponding to the geometries to be simulated described in Table 3. The starting point is the geometry of the real system designed, built, and tested by the research group GISEAC in the facilities of the Technological Units of Santander. Additionally, three improvement proposals are presented where the reflection area is varied to determine the performance, where changes in the angle of incidence and the width of the reflection sheet are proposed. The area variation scenarios are made based on the availability of material in the local area of implementation, determining the characteristics of each reflector material, as well as its dimensions and the option of future modification of the actual system. The present analysis will allow identifying the incidence of the reflection area on the performance of the PTC prototype.

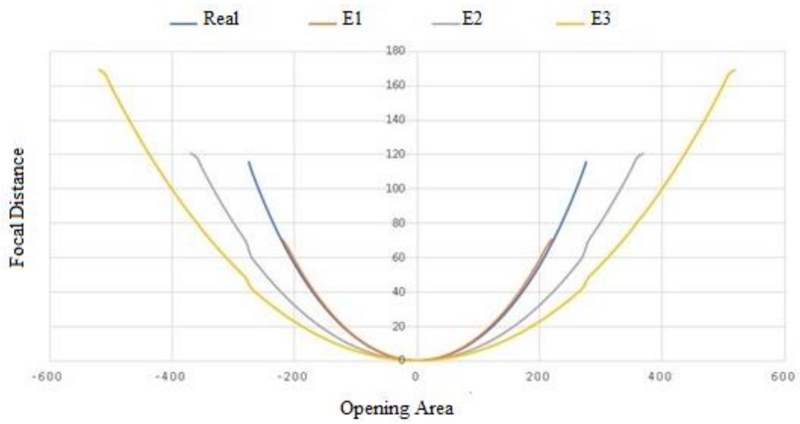


Figure 2. Geometry curves to be simulated

Table 3. Areas of geometries to be simulated

Scenario	Area	Unit
PTC Real	0.9384 m	m
Scenario 1	0.7405 m	m
Scenario 2	1.2681 m	m
Scenario 3	1.7779 m	m

2.4. Soltrace and Tonatiuh modeling

This section presents the simulation process using SolTrace and Tonatiuh software to determine the performance of the PTC prototype and the three improvement scenarios proposed. The software simulates the DNI and the number of rays on a PTC surface and estimates the distributed thermal flux intensity on the reflection and concentration surface. The simulation process in SolTrace is performed in four stages: (i) 3D design of the PTC prototype using Google Sketchup 8, (ii) integration of the 3D design in Google Sketchup 8 with the SolTrace software, (iii) assignment of optical characteristics of the materials and (iv) assignment of DNI and number of rays, then the simulation is performed with the DNI and the number of rays previously defined as shown in Figure 3 and the distributed thermal flux intensity diagrams are obtained. Finally, Figure 3 presents the behavior of the sun's rays for the actual PTC scenario and each of the three proposed scenarios as shown in the graphical interface of the Soltrace software.

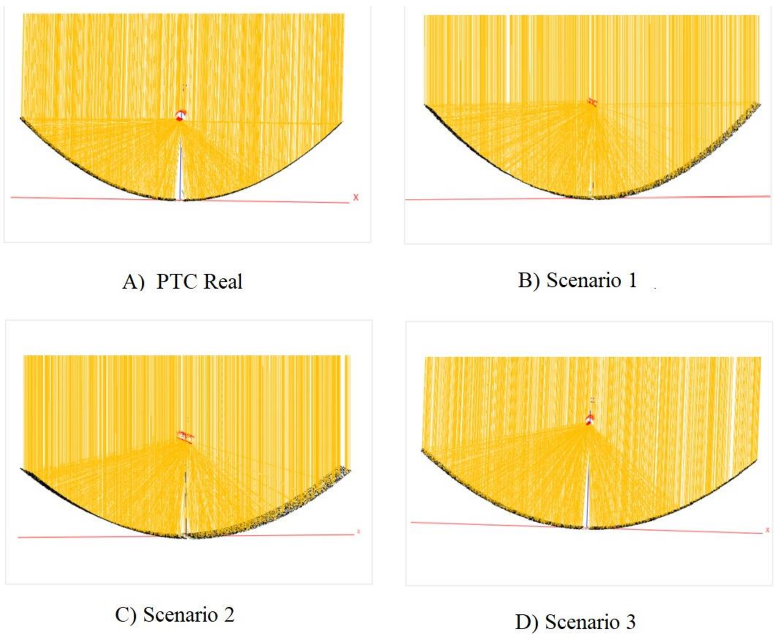
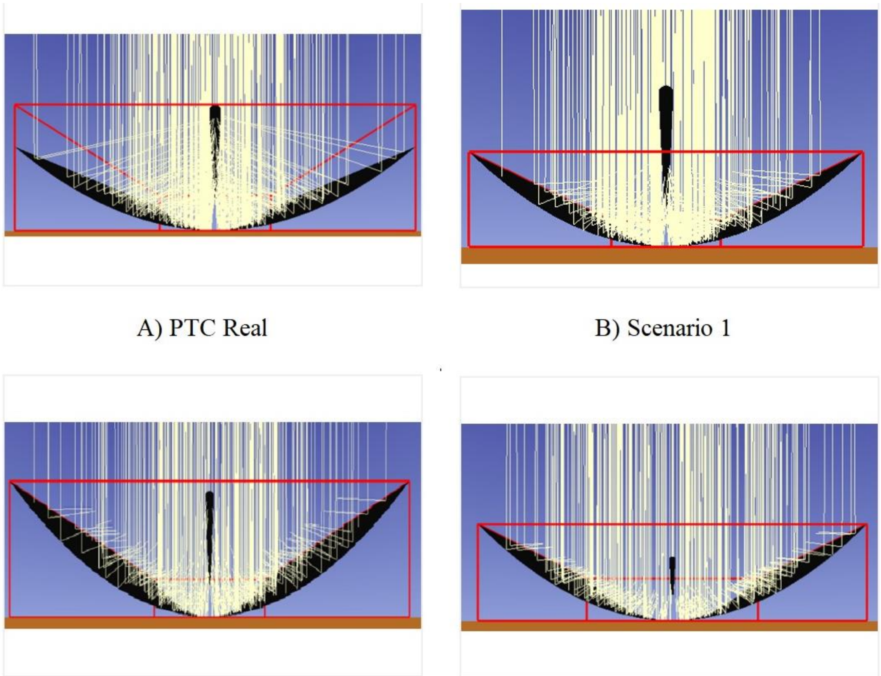


Figure 3. Geometry curves to be simulated

On the other hand, the simulation process in Tonatiuh is also carried out in stages as in Soltrace. However, six stages are required; (i) 3D design of the PTC geometry in the Tonatiuh interface, (ii) definition of the solar position (Tonatiuh, unlike Soltrace, allows through the Sun Earth Tools, to know the solar position for different hours of the day), (iii) define the optical reflection characteristics of each component, (iv) define the refraction characteristics of each component, (v) define the DNI and the amount of rays, and (v) define the PTC zone where the distributed thermal flux intensity map is to be obtained. Finally, the necessary simulations are saved and run. As with the Soltrace software, Figure 4 presents the sunshine behavior for the real PTC scenario and each of the three proposed scenarios as shown in the graphical interface of the software.



C) Scenario 2 D) Scenario 3

Figure 4. Geometry curves to be simulated

3. Results and discussion

The PTC prototype studied is simple and with a decentralized application, built under the appropriate technology paradigm, and has solar tracking to reflect the radiation at the concentration point in a linear way formed by a receiver tube. After analyzing the results of the simulation process in Soltrace software, Figure 5 presents the concentration ratio (CR) weights determined by applying Equation 3 presented in Section 2.2 with the information obtained from the distributed flux intensity maps (Figure 6). Of the four scenarios evaluated, Scenario 1 presents an increase of 2.041 % in the CR value of the actual PTC and about 9.5 % in the CR value of the other scenarios evaluated.

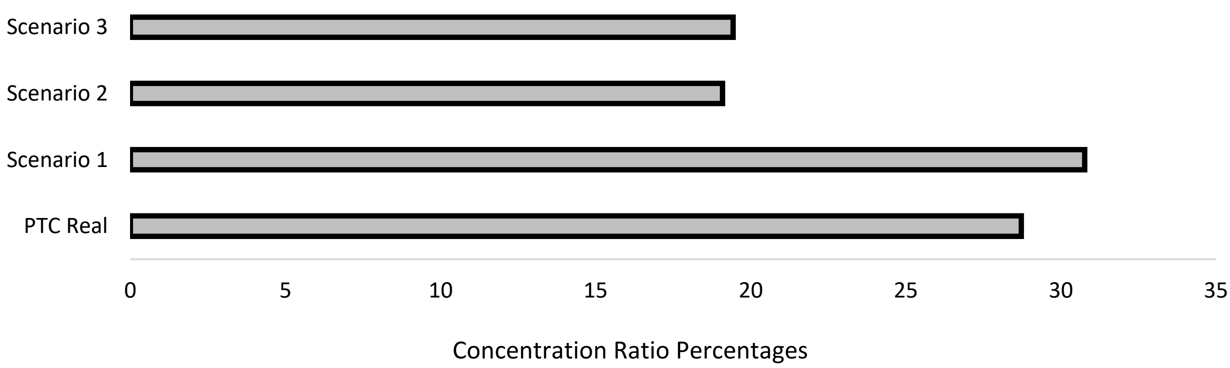


Figure 5. Comparative graph of the concentration ratio percentages in the simulations performed with SolTrace

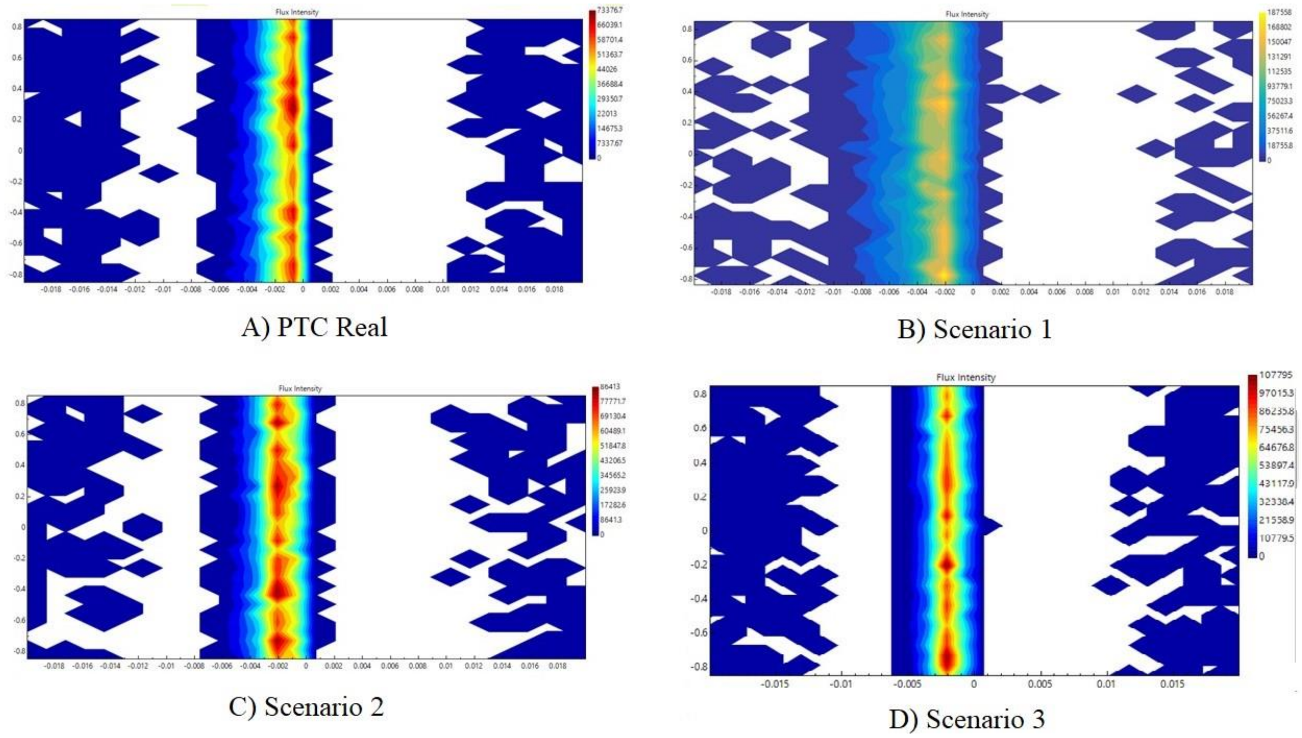


Figure 6. Average flux maps generated by the receiving field applying SolTrace for each scenario

On the other hand, the same process to determine the CR value that was performed for the results obtained by SolTrace was performed for the data obtained for the Tonatiuh simulations. Figure 7 shows the graph with the daily average CR percentages for each of the simulated scenarios with the information obtained from the distributed heat flux maps presented in Figure 8. It is important to mention that the simulation process in Tonatiuh was carried out for a time interval of one hour for an hourly range from 8 am to 5 pm. Of the four scenarios evaluated, Scenario 1 shows an increase of 1.841% in the CR value compared to the actual PTC and an increase of about 9.8 % in the CR value compared to the other scenarios evaluated.

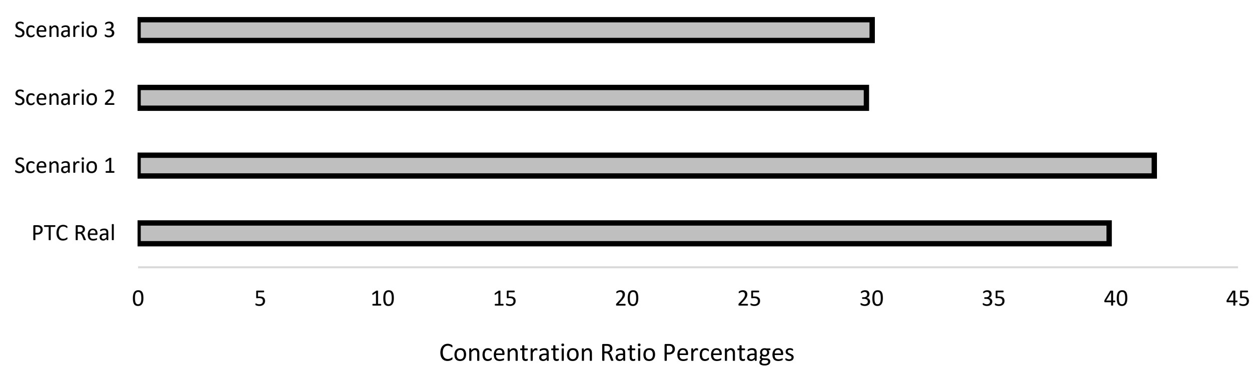
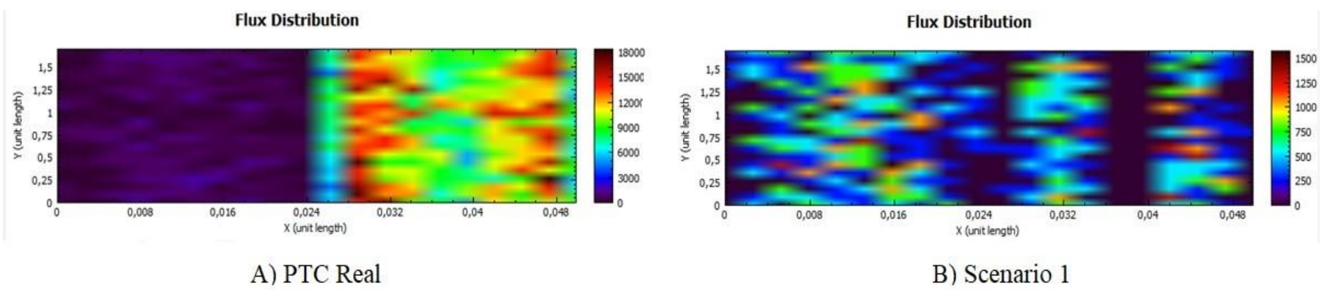
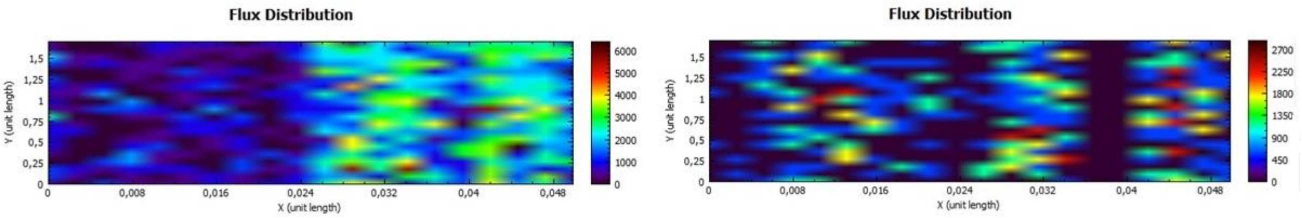


Figure 7. Comparative graph of the concentration ratio percentages in the simulations performed with Tonatiuh





C) Scenario 2 D) Scenario 3

Figure 8. Average flux maps generated by the receiving field applying Tonatiuh for each scenario

The results in Figure 9 show the comparison of the concentration ratio averages of the 4 scenarios evaluated. It can be observed that SolTrace presents lower CR levels with respect to TONATIUH, but the trend in the variation is maintained for both, i.e., in both scenarios Scenario 1 presents higher percentages in the CR value with respect to the scenario corresponding to the Real PTC. Additionally, it can be highlighted that the CR is directly affected by the increase of the reflection area in the collector.

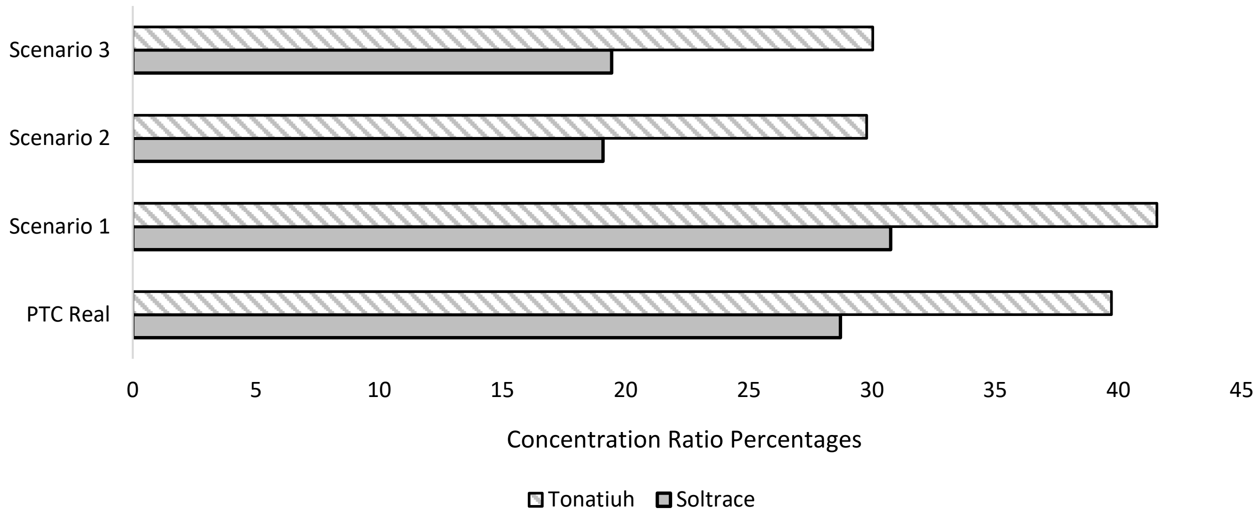


Figure 9. Trend of mean concentration ratio between Soltrace and Tonatiuh software

Additionally, Figure 9 shows that the variation of the CR percentages for the results of the simulations in Soltrace and Tonatiuh presents a similar difference between the evaluated scenarios. The main conclusions are presented below:

- Higher values are observed in the results resulting from the simulation in Tonatiuh. However, the average difference between the results obtained in each of the scenarios with respect to Soltrace is 10.77%.
- It is evident that the smaller the size of the parabola of the main reflection field, the higher the value of CR.
- The difference in the values obtained when applying the algorithms of the MTCR method of each of the softwares, the results confirm an accuracy in predicting which of the scenarios presents a higher level of CR percentage.

On the other hand, the efficiency of the different scenarios evaluated was developed by applying Equation 2 and using the average flux value generated by the mirror field (Q), provided by each of the simulations. The trend of the behavior of the Q value for the simulations developed in Soltrace and Tonatiuh is presented in Figure 6 and Figure 8 respectively. Figure 10 presents a graph comparing the performance results obtained in each of the scenarios evaluated by applying the Soltrace and Tonatiuh software. From the results obtained we can conclude:

- That as the aperture of the PTC parabola increases, the system performance decreases, i.e., the larger the aperture and the larger the area, the lower the system performance.

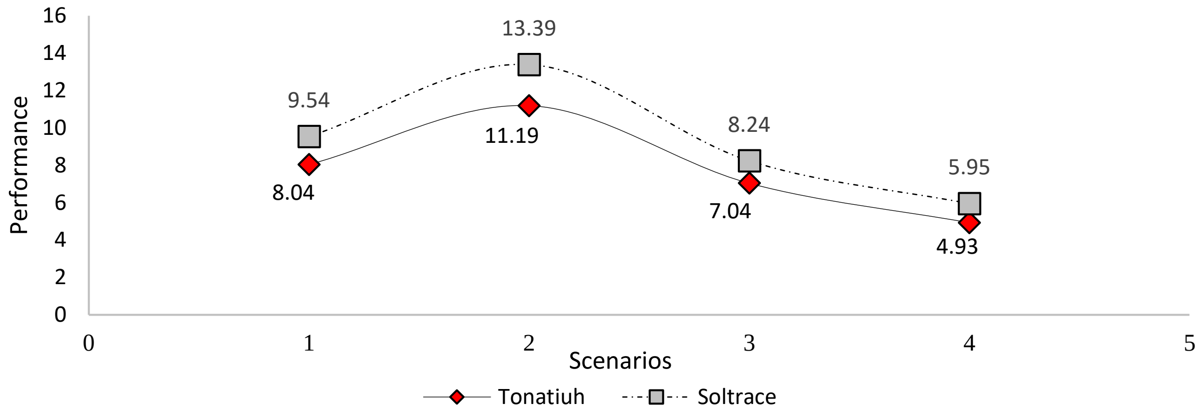


Figure 10. Comparison of performance values of simulations using SolTrace and TONATIUH

On the other hand, in the year 2021, an experimentation process was carried out with the real PTC inside the facilities of the Technological Units of Santander by personnel of the GISEAC research group and they estimated that the performance of the system was 14.85 % [30]. In this context, the performance value of the experimental process is compared with the scenarios evaluated in the Soltrace and Tonatiuh softwares as shown in the following table. Figure 11. From the results obtained we can conclude:

- There is a difference of 5.31 % and 6.81 % between the results obtained by the Soltrace and Tonatiuh software respectively, compared to the performance value of the experimental process. However, the tendency in all the scenarios is the same in the results, so it can be assured that the results obtained do not allow us to know the real value of the experimental process, but, they allow us to evaluate the incidence in the modification of geometric parameters of the PTC in the performance of the device.
- The difference in the results obtained by the two tools may be due to the different mathematical models used to generate the calculation algorithm of the software.

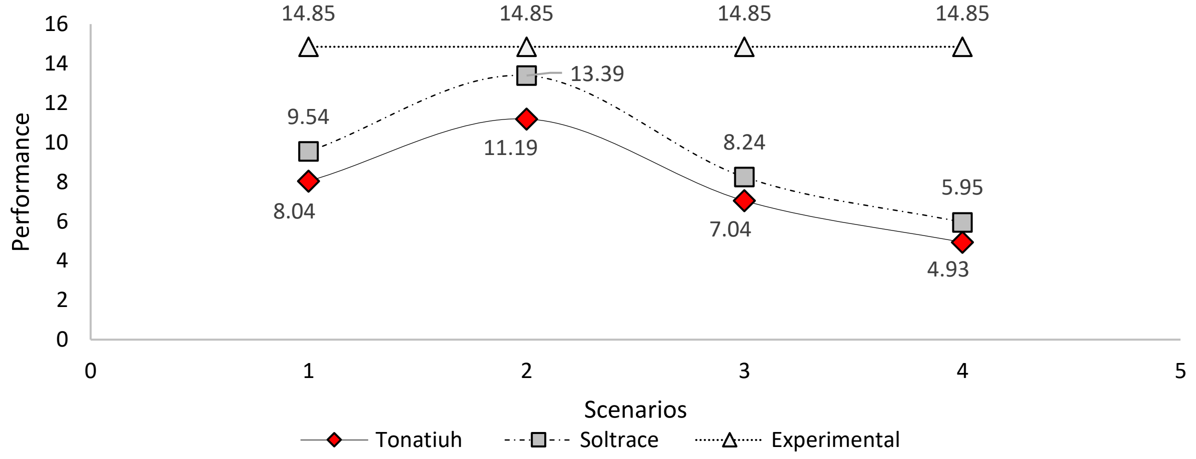


Figure 11. Comparison of the difference between real system performance and simulations using SolTrace and TONATIUH

Finally, Figure 12 presents the percentages of difference between the value obtained from the experimental process previously performed by [30] and the values obtained in each scenario evaluated. From this, we can highlight:

- The performance obtained from the simulations in Soltrace presents percentages with respect to the value obtained from the experimental process that varies as follows: 5.31% for the scenario that simulates the real PTC, 1.46% for Scenario 1, 6.61% for Scenario 2 and 8.9% for Scenario 3. The most unfavorable conditions are presented in Scenarios 2 and 3, while the scenario with the best conditions is Scenario 1, where it is proposed to reduce the PTC parabola. Thus, there is a direct impact on system performance, based on the fact that the larger the PTC parabola, the lower the system performance.
- The performance obtained from the simulations in Tonatiuh presents percentages with respect to the value obtained from the experimental process that varies as follows: 6.81% for the scenario that simulates the real PTC, 3.66% for Scenario 1, 7.81% for Scenario 2 and 9.92% for Scenario 3. The most unfavorable conditions are presented in Scenarios 2 and 3, while the scenario with the best conditions is Scenario 1, where it is proposed to reduce the PTC parabola. Thus, we can reaffirm what was previously expressed in the results of the Soltrace software, which also shows a direct impact on system performance, based on the fact that the higher the PTC parabola, the lower the system performance.

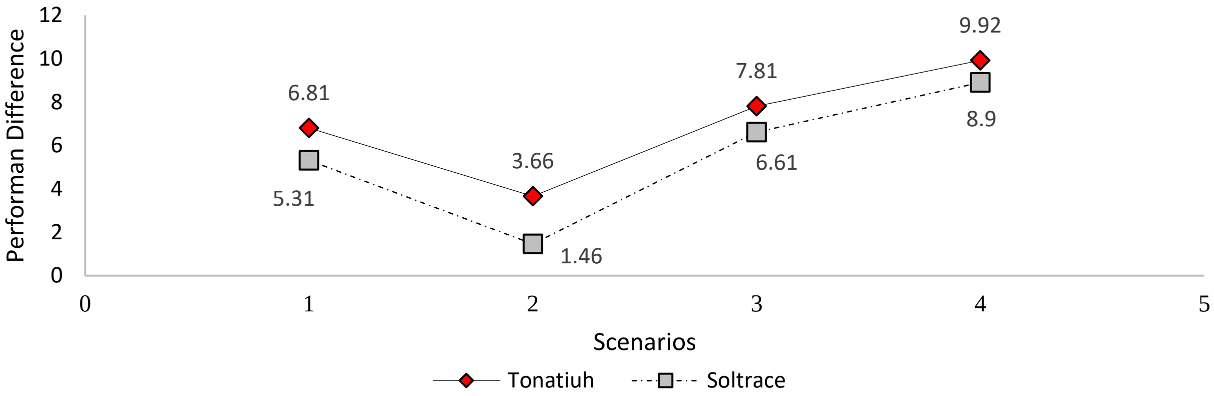


Figure 12. Comparison of the difference in real system performance and simulations applying SolTrace and TONATIUH

4. Conclusions

The use of solar collectors in the world, both at industrial and residential levels, has stood out in recent years with the renewal of discoveries in the field because of its advantages in terms of economy in its implementation and high efficiency shown by various authors in the literature consulted, the handmade prototype made by the GISEAC group of the Unidades Tecnológicas de Santander is taken as a starting point to evaluate its optical efficiency through simulations executed in widely known specialized software (Soltrace and Tonatiuh) allowing to improve this efficiency by redesigning the device. In conclusion, the most important results achieved are:

- The concentration ratio (CR) increases with decreasing area and PTC reflection parabola, where the percentages vary around 10.5 to 11 % for both Soltrace and Tonatiuh data.
- The optical efficiency of the base prototype is evaluated in both softwares, identifying through the literature that it is possible to obtain results with higher value by modifying the geometry of the parabolic surface and observing its higher ray absorption with an edge angle of 90° and considerably decreasing the aperture width of the prototype, showing a significant increase of this performance. This information corroborates the data yielded in the simulations in Tonatiuh for the average of a daily working interval showing an increase of 3.66% and in Soltrace of 1.46% for geometry 1 with respect to the real PTC.
- Additionally, the Soltrace tool provides results with a higher level of precision and accuracy against the known data of the actual PTC performance value, while Tonatiuh tends to be less precise and accurate than Soltrace. The difference between the data obtained is on average 1.8%. This allows us to affirm

that the tools used are reliable in determining the performance of devices based on their geometric variation.

Finally, the study carried out allowed the identification of a geometric improvement in the structure of the existing PTC in the Unidades Tecnológicas de Santander by estimating the yields of the different scenarios evaluated. These types of solar systems generally stand out for their adaptation to the concept of appropriate technologies, which manage low construction and maintenance costs, favoring their application in impoverished areas.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

The contribution to the article is as follows: B. E. Tarazona-Romero, N. Y. Castillo-Leon, J. G. Ascanio-Villabona, M. A. Duran-Sarmiento, Pamela Hulse and C. G. Cardenas-Arias; 3D modeling and study design; B. E. Tarazona-Romero, N. Y. Castillo-Leon, J. G. Ascanio-Villabona: simulation and data collection; B. E. Tarazona-Romero, M. A. Duran-Sarmiento, Pamela Hulse: analysis and interpretation of results; B. E. Tarazona-Romero, N. Y. Castillo-Leon, C. G. Cardenas-Arias: draft writing. All authors approved the final version of the manuscript.

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