CPC solar collector modeling: ray trace studio as an alternative fabrication assessment

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Abstract: In the solar energy area, the technological progress that has brought the development of compound parabolic concentrators (CPC) and their diversification in their applications are well known and has been widely extended nowadays. Regardless of this diversification, the methods used for their manufacture evaluation have not had relevant modifications in recent years. In manufacturing methods, some processes such as the rolling of the reflective sheet or the way of assembling it on its structure, are typically by hand accompanied with errors, so they degrade the efficiency of the concentrator; in consequence, the full potential to concentrate solar power is uncertain. In this study a proposal for the evaluation of the CPC collector is presented, in which a 3D-Molded collector of a 1-sun concentration was assessed, such collector is widely used in photocatalytic processes. To demonstrate the effectiveness of the proposed fabrication assessment, a Monte Carlo ray tracing evaluation was carried out to the compare collectors, obtaining a relative effectiveness of 95% on the 3D-molded CPC against an 82% of a handcrafted CPC, both compared to the ideal 1-sun collector (100% efficiency factor).

Keywords: CPC manufacture, 3D printer, photogrammetric technique, photocatalytic reactor, solar concentrator.

Introduction

In the exploitation of solar energy field, the technological progress that has brought the development of great ideas of different solar collectors and concentrators, are well known. These systems are able to generate a high concentrating ratios (10-58 suns) to produce heat and thus raising temperature for solar process heat applications (Saste et al., 2016) or for its use in the emerging concentrating photovoltaic technology (CPVT) (Guiqiang et al., 2014), three-dimensional concentrators for photovoltaic applications have reached close to 6 suns of concentrating ratio (Van Dijk et al., 2015). In particular, the compound parabolic concentrators (CPC's) are non-image collectors, who have the capability of reflecting to the absorber all of the incident radiation within its boundaries. It consists in a parabolic geometry structure made of a reflective aluminum sheet surface, built by the combination of two symmetric parabolic segments. Suitable to collect the incoming radiation energy from the sun, seizing the UV, visible and infrared spectrum. The parabolic surface follows the shape of a given evolve enabling the entering radiation reach the collector aperture within an acceptance angle according to the design dimension and the rate concentration that is required (Kalogirou, 2014).

The CPC's and the diversification in their applications has been highly studied, such as for skylights in buildings (Ulavi et al., 2014) or photocatalytic processes to degrade microorganisms and persistent contaminants in wastewater, where in both cases low concentrations are required (1-2 suns) (Rodríguez et al., 2004). The objective of CPC collector is to capture all possible solar radiation with an angle of incidence less than the half aperture angle to be reflected towards the receiver within its aperture area (A_a) provided for such concentrator (Gálvez et al., 1985). Whereas, a CPC photocatalytic reactor consists of a tubular collector configuration that focus all the radiation that reaches the CPC to glass tubes, where wastewater flows through the entire tubular-receiver to be decontaminated trough a chemical process. The most used material to form the reflective surface of the collector, consists of silver metallic foil-polymer or high specular reflectivity aluminum sheets, the latter being the one that have given the best results (Fendrich et al., 2018).

Moreover, there are certain advantages in photocatalytic water treatment using these types of concentrators (1-5 suns) that make them special, of which stand out; there is no water heating since exhibit a temperature range of 40°C - 87°C (because of the low solar concentration ratio) and so there is no vaporization of possible volatile compounds, allowing therefore the chemical processes without inconvenience (Blanco et al., 1999). In addition, for this water treatment applications, solar tracking is not required (because of the wide acceptance angle) which reduces costs (Gálvez, n.d.).

With the purpose of develop a suitable design of a CPC, two main parameters need to be taken into consideration: the acceptance angle (θ_a), and the concentration ratio (CR). The acceptance angle defines the angular amount of radiation to be concentrated in the tubular arrangement, while the concentration ratio describes the CPC's capability to concentrate solar energy. Having the special case when θ_a = 90°, so that the CR = 1, and all the radiation that reaches the opening area of the CPC is captured towards the receiving tube. The CR is given by the aperture area A_a divided by the tubular receptor area ($A_r = 2\pi r$) (Blanco-Galvez et al., 2007). This relation is usually expressed in units of "suns", where the concentration of 1 sun is equivalent to a geometric ratio $A_a/A_r = 1$ (Duffie et al., 2006).

In an attempt to optimize the efficiency of CPCs, optical-geometric design and manufacturing methods of these concentrators have been developed, resulting in more efficient assembling alternatives, reducing losses and thus having the maximum exploitation of the collector (Pranesh et al., 2019). However, despite innovative changes in the geometric configurations of the collectors, this is not the case in mechanized manufacturing processes, which can interfere with optical efficiency so that the full capture potential is not reached. This is due to the processes such as the machining of the sheet, which is a handcrafted technique where two sheets are joined forming two parabolas, either by welding them or fixing them with fixtures. This leads to problems with bends or malformations due to hammering or mechanical stress, affecting the initial design and consequently generating losses that affect the expected optical efficiency (Gudekar et al., 2013).

In some studies, the thermal efficiency is investigated from the perspective of the support structure, design and construction where a frame of ribs is used for its setting (Chafie et al., 2016). On other studies (Forman et al., 2015), use assemblies that required joints which generate gaps between them. To mitigate it, they use light concrete shells as support structure instead of the steel frames, which proved its stiffness and fill the gap between the supporting structure and reflecting surface. Furthermore, a study presented by "Meiser et al. (2017) in order to minimize the deviation that occurs from gravity load on mirror shape and to investigate the deformation of the mirror due to gravity load and mounting forces and its effect on the shape of the mirror, where the resulting focus deviation values were evaluated (Meiser et al., 2015, 2017). "Balghouthi et al. (2014) studied the optical and thermal performance for a parabolic trough solar collector (PTSC) by photogrammetric techniques. (Balghouthi et al., 2014).

Recently, Carrillo et al. (2020) achieved a methodology to manufacture this kind of CPC collectors using a Styrofoam mold cut by hot-wire technique, obtaining this way the required shape without using mechanical fasteners, where the results were analyzed by a photogrammetric technique (Carrillo et al., 2020). In this context, the innovative methodology was used in the present paper as an alternative 3D-Printed Mold and a further Monte Carlo ray trace evaluation, looking to contribute to diminish the misalignment problem caused by the manufacturing of the collector´s concentrator and at the same time a complementary ray trace evaluation, confirming the collecting surface effectiveness. The technique was developed with a mold manufactured in a 3D printer by means of a 1-sun geometrical ratio CPC design. By the use of a mold, it is possible to eliminate a machining or a manual manufacture in addition to avoid structures or clamps and joints that can deform the parabolic shape of the collector. The proposed technique has the advantage that the reflective sheet of the concentrator will not undergo any kind of contact deformation, since the mold is used to give the form of concentrating parabolas to the aluminum sheet. In addition, by means of polyurethane foam the sheet is compressed against the mold and takes the given shape according to the 3D mold. Obtaining this way, a deformation-free surface which contributes to improve the capture of optical energy and thus, it is possible concentrate and redirect the solar radiation to the CPC focal point with higher efficiency.

In this manuscript, an alternative method to determine the 3D mold technique effectiveness by using two different evaluations is described: 1) Comparing the CPC 3D-molded (ideal) with the handcrafted collector by a photogrammetric optical procedure, in order to establish the real shape, according to the ideal 1 sun concentration. 2) A complementary ray trace evaluation was made to establish the effectiveness concentrating system. The results in increased efficiency of the 3D based manufactured CPC and the photogrammetry and ray trace performance evaluations are presented.

Materials and methods

The method to manufacture the collectors on the 3D printed mold consists of two stages. The first one is about the design, 3D printing and construction of the CPC. On the other hand, the second one describes the assessments made to the collectors in the manufacturing efficiency using Monte Carlo ray tracing.

CPC design

The design is performed using equations 1 and 2 for the involute shape and equations 3 and 4 for the parabola profile on a xy plane, where r is the external radius of the receiving tube, while the rim angle φ is the angle between the axis and a tangential line from the focus to the physical edge of the concentrator. Finally, θ_a is the acceptance angle of the collector (Salgado-Tránsito et al., 2015). Figure 1 shows the design for the CPC of $CR = 1\ sun$ for a tube with external $r = 16.1\ mm$, while the CR is given by equation 5 where an angle of 90° was defined.

$$x = r\ (sen\varphi - \varphi\cos\varphi) \quad \textbf{(1)}$$

$$y = -r\ (\varphi sen\varphi + \cos\varphi) \quad \textbf{(2)}$$

with $0 \leq \varphi \leq \pi/2 + \theta_a$

$$x_2 = r\ (\varphi sen\varphi - A\cos\varphi) \quad \textbf{(3)}$$

$$y_2 = -r\ (Asen\varphi + \cos\varphi) \quad \textbf{(4)}$$

where $A = \frac{\left[\frac{\pi}{2} + \theta_a + \varphi - \cos(\varphi - \theta_a)\right]}{1 + sen(\varphi - \theta_a)}$ with $\frac{\pi}{2} + \theta_a \leq \varphi \leq \frac{3\pi}{2} - \theta_a$

$$CR = \frac{1}{sen\ \theta_a} \quad \textbf{(5)}$$

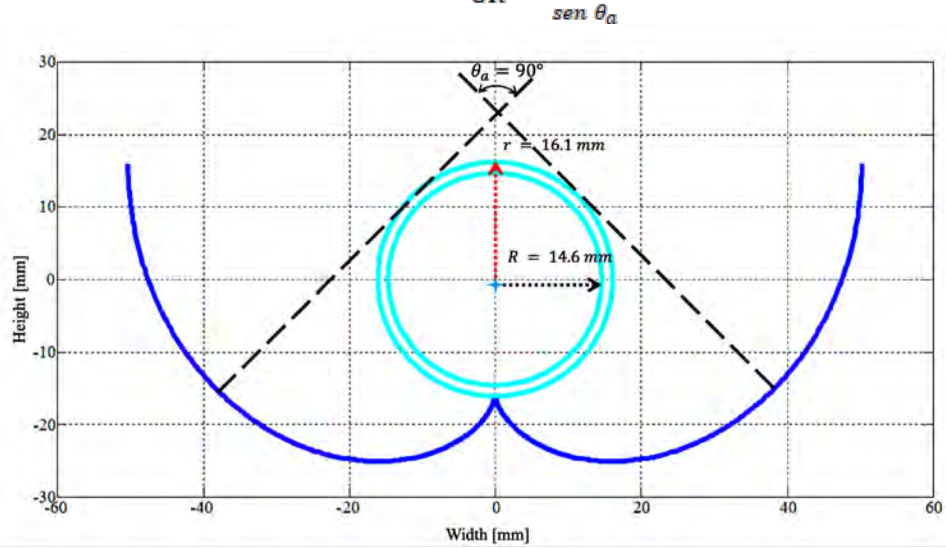


Figure 1. Ideal 1-sun CPC design for a 32 mm photocatalytic reactor glass tube diameter.

3D printer and software:

From the 2D generated involute, the 3D parabolic design that serves as a mold for the CPC is performed. For this activity, AutoCAD® 2019 was used where the scheme goes from 2D evolve to become the 3D mold of the collector. The design of the mold was made in 4 assembled parts (male-female), each piece has dimensions of 99.4 x 330 x 40.9 mm (limited to the 3D printing parameters), and thus reach the length required to cover the entire CPC receiver tube (1320 mm) used commonly in a photocatalytic reactor (low concentration e.g. 1-Sun). The mold manufacturing process was carried out in the 3D printer (ADEN®), with a 1.75 mm PLA filament thickness. On the other hand, to achieve that the highly reflective aluminum sheet takes the geometric shape of the printed mold, a steel container was developed. This container has internal dimensions of 1320 x 102 x 50 mm, with a wall thickness of 5 mm. The mold container provides the adequate setting to maintain the mold and the aluminum sheet together under tension, causing the latter take the form of the CPC designed.

Polyurethane foam

In order to obtain the appropriate folding of the CPC laminate, polyurethane foam was added into the container with the aluminum foil and the mold previously placed. The foam fulfills the function of exerting pressure on the reflective sheet against the mold as it expands throughout the container, thus taking the shape of the desired collector without using fasteners. The process to produce the polyurethane foam is done in a simple way and consists of two part components (A and B) which are mixed in a 50:50 ratio and has a reaction time of 20 s to start expanding, while the drying-time varies from 4 to 6 hours depending on the temperature and density of the components. 60 ml of each resin was used to cover the volume of the container to press the sheet against the mold.

Compound Parabolic Concentrator construction

Figure 2 shows the manufacturing methodology used. The flat surface of the 3D printed mold is placed inside the container, in such a way, that remains in contact with the bottom of the mold recipient (Figure 2a). Subsequently, the aluminum sheet is placed on the mold (previously cut according to the calculated CPC design) thus adjusting to the parabolic design (Figure 2b). Once the sheet and mold are inside the container, the A-B polyurethane foam mixture is added and immediately after, the container is closed (Figure 2c). As a chemical reaction result of the A-B polyurethane mixture, it turns into a foam that expands, generating pressure on the anodized aluminum sheet against the mold, copying the required CPC profile (figure 2d). Finally, the lid of the container is removed, and the mold is separated from the collector. In this way, a sheet with the shape of the parabolic involute and with a polyurethane foam base is obtained (Figure 2e).

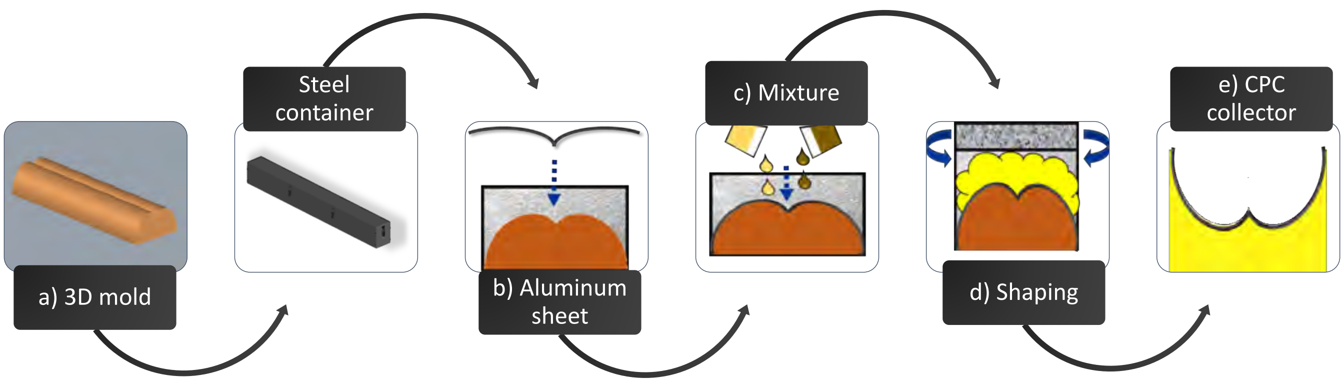


Figure 2. Procedure for the manufacture of the CPC. a) the 3D-printed mold is introduced into the container, b) the anodized aluminum sheet is placed on top of the mold, c) the polyurethane foam mixture is poured, d) immediately closed where takes place the reaction and drying time and then e) the CPC is obtained.

Evaluation of the CPC efficiency

A photogrammetry methodology was developed in order to validate the result of manufacturing the collector and so evaluate the imperfections in the surface sheet shape-CPC by machining or mechanical stress. As is illustrated in figure 3 the methodology consists of performing a three-dimensional surface reconstruction by means of photographs taken to the object to be studied. The modeling of the images obtained from the CPC was carried out through the software Caesoft® (v. 2016.0.5.1718). The technique was performed using a 2 mm dot pattern (figure 3a) printed on vinyl with 5 mm separation between each dot (previously defined by the software itself), which was placed on the entire surface to model (figure 3b), so that the points follow the form of the CPC studied (figure 3c). After that, pictures from different positions around the pattern were taken with a Nikon® D3000 camera equipped with AF-S Nikkor 18-55 mm lens. Afterwards, the images obtained were treated and analyzed by meaning the Photomodeler software (King et al., 2020; Weber et al., 2014).

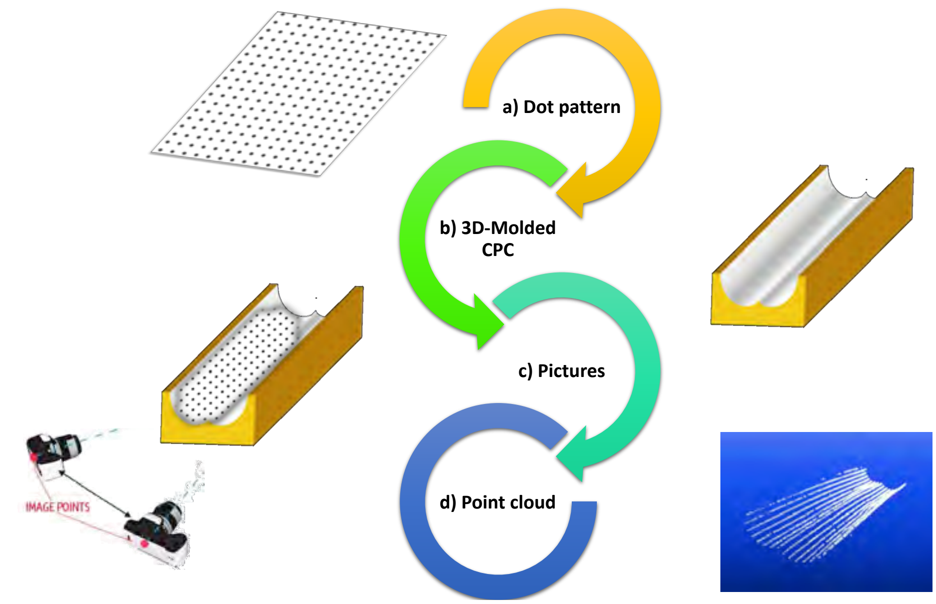


Figure 3. Photogrammetry technique: a) dot pattern placed over the b) CPC 3D-molded and then c) a series of pictures are taken to process in the PhotoModeler software and thus d) a point cloud is generated.

Analysis

Two type of evaluations were made in order to evaluate the construction of the 3D molded collector: 1) A photogrammetric evaluation using a mathematical algorithm and a 2) Monte Carlo ray trace analysis of the structure basis on the obtained data.

The closest dot algorithm was used to evaluate the CPC 3D surface, obtained by mechanized with Polyurethane foam and thus compare it with a CPC of 1 sun geometric concentration ideal design (Figure 1). This mathematical evaluation uses the dots array in x, y and z axis given by the PhotoModeler software and group the closest dots into clusters. The algorithm begins with an arbitrary starting data points. The neighborhood of this points is extracted using a distance (reference, in this case the 1-sun ideal CPC shape), if there are a sufficient number of points within this neighborhood then the clustering process starts and the current data point becomes the first point of the new cluster. Otherwise, the point will be labeled as noise. For this first point in the new cluster, the points within a given ε distance neighborhood also become part of the same cluster. This procedure of making all points in the ε neighborhood belong to the same cluster is then repeated for all of the new points that have been just added to the cluster group. After all dots are assigned, the centroids in the clusters are fixed. Finally, the closest clusters' centroids are compared to the 1-sun ideal CPC reference. These results are presented in the Figure 5. A similar methodology was used by Carrillo in 2020.

Evaluation with Ray Tracing software

There are several methods to evaluate the collector's surface by using pattern reflection deflectometry (Meiser et al., 2014; Peña-Cruz et al., 2014; Weber et al., 2014; Zhu et al., 2015), photogrammetry technique (El Ydrissi et al., 2019; Skouri et al., 2015), even measuring the flux distribution using simulated ray-trace model (Schiricke et al., 2009) as is the case in Terrón et al. (2017), where they make use of the Tonatiuh ray-tracing software to simulate the interaction between solar rays and solar concentrator to quantify the amount of energy that impinges into a CPC used as a residential water heater (Terrón-Hernández et al., n.d.) and as Giovinazzo et al. (2014) (Giovinazzo et al., 2014) use this software to simulate the course of the year into a photovoltaic termal collector (PVT) and compare the results against a mathematical studio to assess the impact of each change in the PVT. Either one is effective, and is dependent on the particular purpose of the object under test. In this context, in addition to the closest point algorithm procedure, another feasible assessment proposal with the data obtained is an advanced ray tracing study. The PhotoModeler software produces a 3D surface layer model using the dot pattern of the images obtained according to the 1-Sun CPC Collector actual size. Afterwards, a .STL file is generated in PhotoModeler and exported to the design software AutoCAD®. In order to provide a real size and so manipulate it in Tonatiuh, a pretreatment in AutoCAD® was made to the layer model where a 5 mm thickness given to the surface, an aluminum solid material and a refined mesh model was assigned to the collector layer surface. Refinement on the surface mesh helps to mold smaller sections with less effect on the overall shape of the model. A mesh model consists of vertices, edges, and faces that use polygonal representation and it's applied to define a 3D shape model.

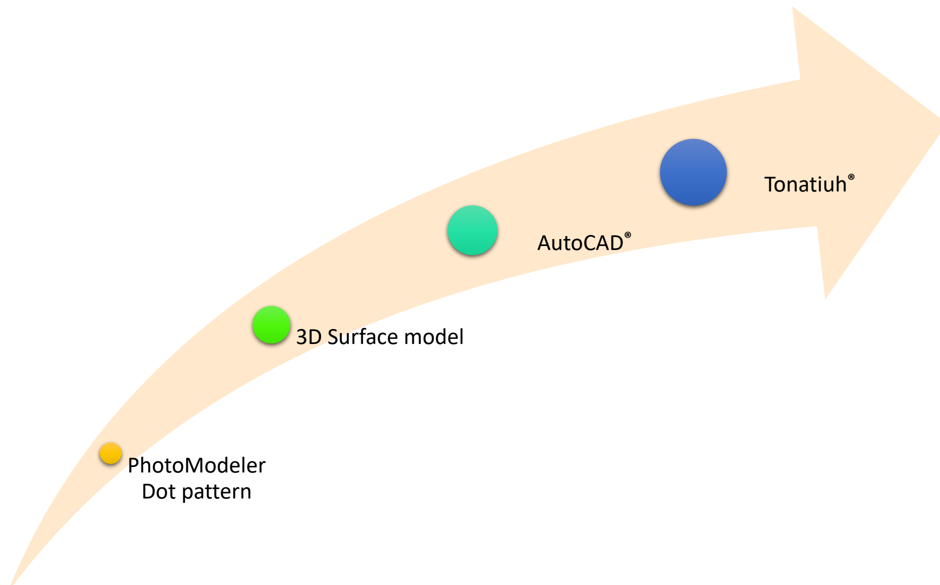


Figure 4. Scheme showing the flux chart to process the dot pattern obtained in PhotoModeler trough the AutoCAD software and so finally simulate the ray trace model in Tonatiuh.

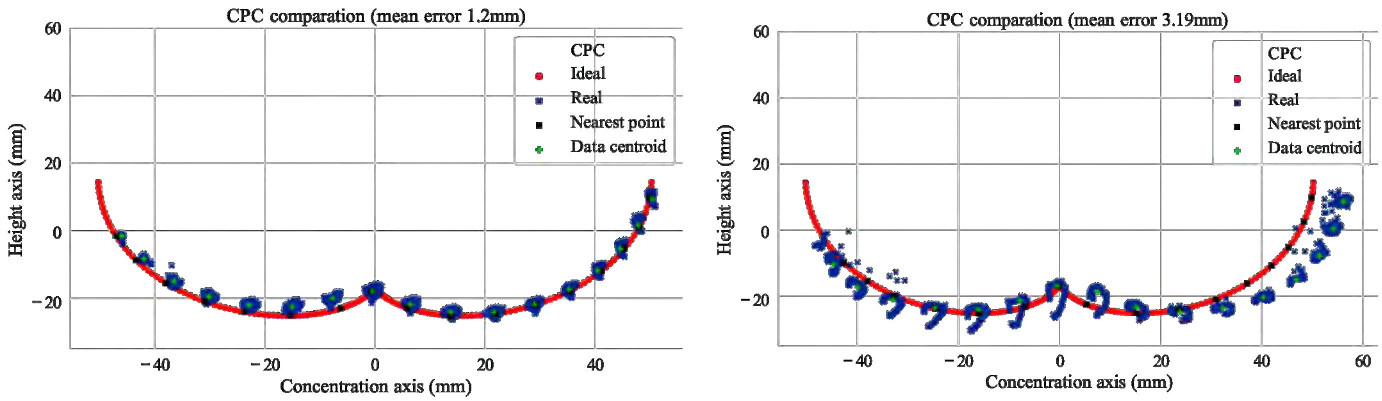
Subsequently, a file with extension .STL of the model was generated, which can be exported to be used in the Tonatiuh® software (v. 2.2.4). This software is a Monte Carlo ray tracer for optical simulation of solar concentration systems, a flux chart for the procedure is shown in figure 4. Parameters such as incident solar power, minimum, maximum and average flux, uniformity and centroid location are visualized in the Tonatiuh environment. It allows to compare the 3 studies; ideal, 3D-molded and manually manufactured 1-sun CPC collector on its collecting efficiency by simulating the optical behavior of the system. For this study a 21.00 latitude and -102.00 longitude sun position as well as an inclination of the collectors of 21° were included as simulation parameters. In this regard, absorbance in the receiver tube of 96% and a reflectance of 95% were established as optical parameters according to the standard material specification.

Results and discussion

Closest dot algorithm

The Figure 5a shows the CPC 3D mold data (blue dots) and its mean absolute error acquired by using the photogrammetry technique and represented in single plane comparing to the ideal geometric 1-sun CPC shape (red dots line) elaborated in Matlab software in accordance with equations 1-5. Likewise, the Figure 5b exhibits the CPC handcraft manufacturing comparison specifying its mean absolute error, in which construction techniques such as bending, punching and manual bending were used. The 3D-mold CPC mean deviation indicated in the Figure 5a is barely 1.2 mm which is a remarkable, since a novel and cheap procedure was followed according to the manufacturing methodology shown in Figure 3. This shows that the proposed manufacturing technique using a 3D mold and polyurethane foam is adequate and considerably approximated to the ideal shape of the analyzed CPC.
On the other hand, the results show a major mean deviation when the handcrafted construction methodology was used with a 3.19 mm error. As shown in Figure 5b the curved shape of the evolve was not achieved specially at the CPC edges, it can be attributed to the hand-made manufacture technique.

Regardless of the mean absolute error (MAE) in 3D-molded CPC according to its dimensions and shape, it becomes negligible. This MAE can be attributed to two causes, 1) the length of the CPC (1300 mm) which is considerably large and 2) the data centroids, that is a high data number given by the software itself. This is due to the fact that the dots pattern is very close from one point to another (5 mm) for an optimal surface scan, moreover the CPC shape is very curved on its edges due to its parabolic form, which makes it difficult for the software to process the images. It should be noted, however, that there is an inherent uncertainty in the data collected by the photogrammetric technique, which is attributed to different factors that determine the accuracy of a photogrammetric project. The main factors affecting accuracy are: photo resolution, camera calibration, angles, photo orientation, quality photo redundancy and targets/marking precision. Aspects like focal length, distortion lens, number of pixels, angled photos for more detail, number of photos, target size and software precision marking targets by pixel are example of them.



(a) **(b)**

Figure 5. Graphs showing the ideal CPC one sun (red dotted line), compared to the 3D-mold technique (a) and to the handcrafted technique (b) and their calculated mean error respectively.

Nonetheless, an estimation of the root mean square standard error (RMSE) was calculated using the data collected by the PhotoModeler software that provides a set of residual points in pixels from the 3D surface layer model. The RMSE value calculated is ± 0.01 px or 0.002 mm. Thus, a general project error data is considerate for the reported result.

Result of ray tracing analysis

Using Tonatiuh® software, a Monte Carlo ray trace studio were simulated for surface models in order to evaluate the concentrating performance. Figure 6 shows the ray trace simulation for a 21.00 latitude and -102.00 longitude sun position to compare the ideal, 3D-mold and handcrafted manufactured CPC.

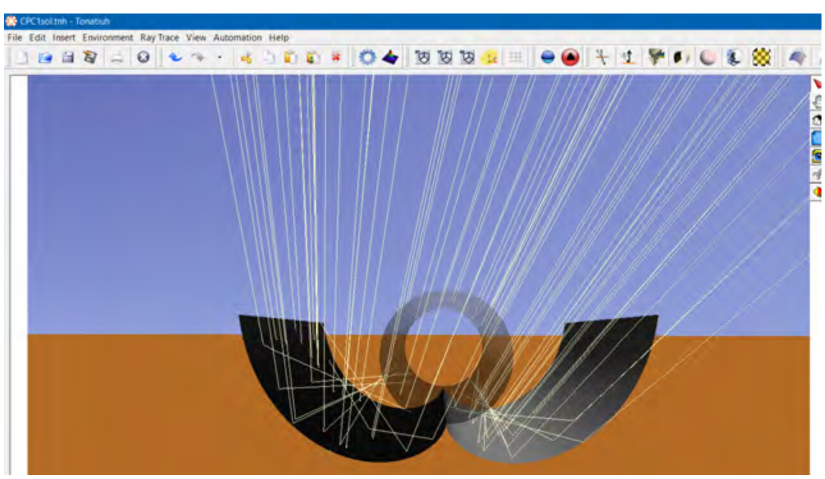


Fig. 6. Ray trace simulation environment in Tonatiuh software for all CPC collector configurations.

The ray tracing studio consists in estimate the four-day seasons positions (solstices and equinoxes) to demonstrate and compare the 3D-molded and the handcrafted collector's functionality and efficiency against the 1-sun ideal collector, measuring hourly the simulated incident radiative flux collected in the receptor tube during each of the four days (vernal equinox, summer solstice, autumnal equinox and winter solstice), the results are shown in Figure 7.

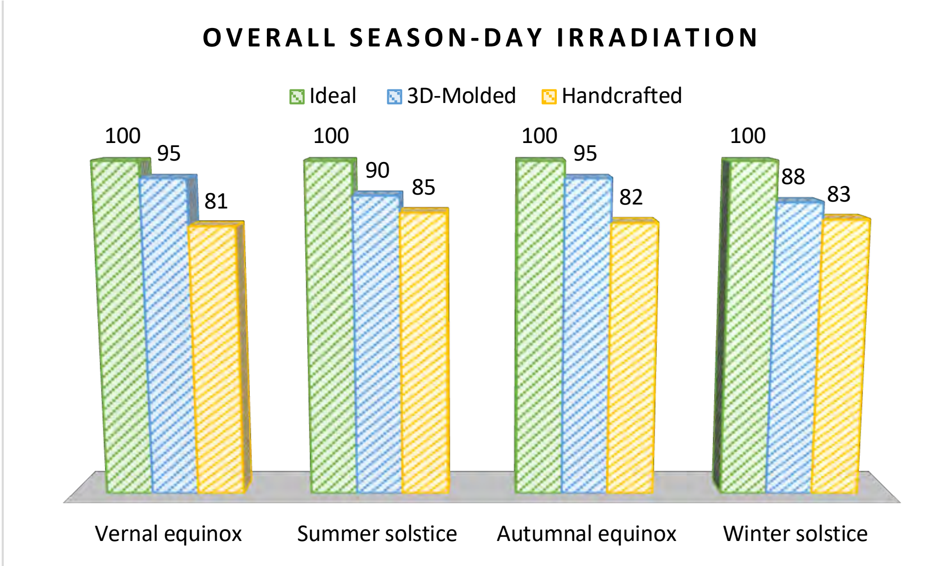


Figure 7. Shows the ideal 1-sun, 3D-Molded and Handcrafted CPC performances for the four sun seasons; vernal equinox (March 21), summer solstice (June 21), autumnal equinox (September 23) and winter solstice (December 23).

The results presented in figure 7 shows the overall season-day sun irradiation (in percent efficiency factor) for the four dates in every collector based on the irradiation integrated. The collecting performance of the 3D-Molded and a Handcrafted CPC are compared with the ideal 1-sun CPC using the result of the area under the curve.
As can be seen in figure 7, the difference between a hand-made and a molded collector is relevant. The methodology for the construction of a proposed CPC (Figure 3) and the one by using conventional methodology showed a higher solar collection efficiency factor for the 3D-Molded over the handcrafted CPC collector. Assuming that the ideal 1-Sun collector have the 100% percent efficiency factor the 3D-Molded and the Handcrafted collectors obtains a 95 % max – 88 % min and an 85% max – 81% min range respectively. Although 3D molded CPC has some errors in the reflective surface, it is close to its shape due to the manufacturing technique. This allows 3D molded CPC to have a considerably better performance than CPC built from mechanical shaping techniques and tools. On the other hand, the graphs in Figure 7 confirms the performance difference according to the manufacturing technique respect to the ideal one, being this the most efficient on the four graphs, followed by the one with the 3D-Molded and lastly the handcrafted collector shape.

Conclusions

In the present study, a CPC 3D-molded was fabricated with the aid of a 3D printer and polyurethane foam and compared to a typical handmade fabrication regarding to an ideal concentrating system. Furthermore, an alternative methodology for the optical evaluation of CPC collectors using ray tracing and reverse engineering was developed, as a case study, the optical performance of two CPCs; the 3D-Molded and Handcrafted manufactured was compared. This evaluation suggests a reliable and economical methodology, because of no accessories or major equipment are required, in addition Tonatiuh is a free access software. The method accuracy was evaluated through a photogrammetric optical procedure and analyzed by a closest point mathematical algorithm. According to the ideal geometrical 1-sun concentration both methods were studied. The results in manufacturing efficiency gives a MAE of 1.2 and 3.19 for the 3D-molded and the handmade CPC fabricated respectively. Additionally, a Monte Carlo ray tracing evaluation was made to support the collector shape assessment, where a four-day sun positions studio, demonstrates under different irradiation conditions the overall performance and effectiveness of the 3D-Molded and Handcrafted CPC collectors. Showing that in every day the 3D-Molded collector had a better efficiency than the handcrafted, where a 95% efficiency on the 3D-molded CPC was obtained against the 82% handmade CPC efficiency in the autumnal equinox day i.e., both compared to the ideal 1-sun collector (100% efficiency factor). Even though the low irradiance contribution in the case of the winter solstice the 3D-Molded collector shows the best irradiation collecting results. Both results, reiterate the advantage and effectiveness using this manufacturing methodology. This assessment infers a determinant factor in solar collector's optical performance, especially in low-power concentration due to the limited

UV solar radiation available, e.g. for chemical processes. This implicates that the mechanical manufacture of the CPC shape is an important parameter to collect all the photons required, as for example, in the photocatalytic reactor. It is expected that this new methodology of CPC manufacturing, improves significantly its performance in real applications and trough the ray tracing optical evaluation improve the assessment of this kind of collectors.

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