Optical Evaluation of the Tolokatsin-2020 High-Efficiency Solar Cooker

Eduardo González-Mora[1] and Eduardo A. Rincón-Mejía[2]

[1] Engineering Faculty/Universidad Autónoma del Estado de México, Toluca (México)

[2] Energy Programme/Universidad Autónoma de la Ciudad de México, Ciudad de México (México)

Abstract

In order to cook with solar energy, it is necessary to have a highly efficient solar cooker that captures a great portion of the diffuse radiation. More than 20 years ago, the first solar cookers called "Tolokatsin" (Náhuatl language name meaning "born in Toluca", the city in which they were created) were designed. Nowadays, the Tolokatsin solar cookers work with a three-dimensional multi-compounded solar concentrator based on non-imaging optics, using only mirrors of simple curvature. The original design consists of a concentrator with four pairs of optimally truncated mirrors that allow an excellent operational performance. A further advance has been made to reduce the losses by reflections, by changing the number of mirrors and the solar concentration as predicted recently by constructal law, keeping only mirrors of simple curvature; demonstrated by ray-tracing techniques, where the validation of the new design can be addressed since the optical efficiency was increased 9.4%.

Keywords: optical efficiency, solar cooker, Tolokatsin, ray-tracing

1. Introduction

The world has a serious urgency to provide the necessary resources and means to combat famine, as UN reports estimate that there are around 690 million people in the world suffering from food shortages (United Nations, 2020), and also to drastically reduce the consumption of fossil fuels for cooking. Cooking is a basic need for everyone, practiced everywhere by humankind, and a heat source above 100 °C is needed (Lecuona et al., 2017). Around 28 million Mexicans depend on burning solids for food cooking, usually firewood or charcoal, (globally there are about 3 billion people who eat food cooked with firewood according to the International Energy Agency) (IEA. International Energy Agency, 2018; Rincón Mejía, 2010). Cooking burning any kind of fuel, lead to some problems that must be addressed as body burns, explosions, poisonings, and contamination, just to mention a few, resulting in approximately 3.8 million deaths per year attributable just to household air pollution (World Health Organization, 2018).

For years, the implementation of solar cookers and solar ovens has allowed us to tackle the after-mentioned problems by reducing considerably the burning of any fuel, improving people's quality of life regardless of their age range. Allowing people to cook their food without having to depend on fuels that have an inherent cost and that for the population that is in poverty, the dilemma arises of prioritizing the needs to be covered.

At present, there are a large number of alternatives for cooking with the Sun, from simple devices such as the "box solar cooker", or the implementation of medium concentration systems such as parabolic troughs and parabolic dishes, or even large Fresnel lenses for cooking at higher temperatures (Lecuona et al., 2017; SCI, 2019). These systems present certain problems that have been tried to overcome, such as the implementation of low concentration ratio systems, like the solar panel cookers, "funnel" and its modifications developed by Ruivio (Apaolaza-Pagoaga et al., 2021; Solar Cookers International, n.d.), or even higher concentration ratios as Coccia et al. (Coccia et al., 2017). Some examples of these systems are shown in Fig. 1.

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(a) Solar box **(b) Funnel** **(c) Parabolic dish** **(d) Parabolic trough** **(e) Fresnel lens**

Fig. 1: Main types of solar cookers (González-Mora, 2021). Adapted from: (Solar Cookers International, 2019)

Considering this, the Tolokatsin solar ovens (meaning "born in Toluca" – the city in which they are from – in Náhuatl,) were first designed and built more than 20 years ago. The main difference between the Tolokatsin solar oven with the many other devices designed to cook with the Sun is the use of non-imaging optics that lead to an efficient radiation transfer from the source (Sun) to the objective (receiver). This results in a compact multi-compound system that can achieve high temperatures in little time and with high efficiency (González-Mora et al., 2020; Winston et al., 2005). The direct application of non-imaging optics allowed the applications of Tolokatsin to be extended to other sectors as solar sterilizing (González Mora et al., 2016a, 2016b), diversifying the original line of its design with great success.

1.1. Structure and scope

Recently, authors have predicted that decreasing the number of reflections in the Tolokatsin designs will lead to an optical efficiency increase (González-Mora et al., 2020), so an optical ray-tracing was needed to verify this claim. In the present, optical analysis of the new Tolokatsin-2020 design is performed with ray-tracing software to validate the new design. The Tolokatsin designs have evolved through the years tackling a considerable reduction of the optical losses, keeping in mind the high efficiency and easy manufacturing processes. Section 2 includes a brief description of the Tolokatsin designs, while Section 3 describes the general procedure for the optical analysis with a brief discussion of the results. The present analysis can be used for further thermal analysis to quantify the figures of merit F_1 and F_2 (Collares-Pereira et al., 2018; Funk and Larson, 1998; Funk, 2000) for this solar cooker design.

2. Tolokatsin designs

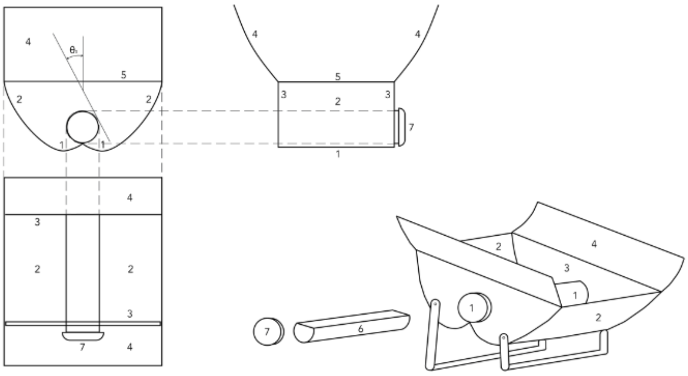
The Tolokatsin solar ovens take advantage of non-imaging optics, where efficient radiation transfer from the source to the objective (receiver) can be accomplished (Winston et al., 2020, 2005), even though sacrificing the sun image (aberration formations). The geometries for all Tolokatsin designs are principally a proper combination of flat in the upper part (Eq. 1) and circular absorber for the lower part (Eq. 2) CPCs profiles, taking into consideration the optimum truncation criterion of three times the acceptance angle, originally stated by Rincón et al. (2009).

$$\begin{cases} x(t) = \frac{(1+\sin\theta_0)\cos t}{1-\sin(t-\theta_0)} \\ y(t) = \frac{(1+\sin\theta_0)\sin t}{1-\sin(t-\theta_0)} \end{cases}, \quad t \in \left(0, \frac{\pi}{2} - 3\theta_0\right) \qquad \text{(eq. 1)}$$

$$\begin{cases} \begin{cases} x(t) = \sin t - t\cos t \\ y(t) = -(\cos t + t\sin t) \end{cases}, \quad t \in \left(0, \frac{\pi}{2} + \theta_0\right) \\ \begin{cases} x(t) = \frac{\sin\theta_0 \cos(t-\theta_0) - \left(\frac{\pi}{2}+t+\theta_0\right)\cos t}{1+\sin(t-\theta_0)} + \cos\theta_0 \\ y(t) = \frac{\sin\theta_0 \cos(t-\theta_0) + \left(\frac{\pi}{2}+t+\theta_0\right)\sin t}{1+\sin(t-\theta_0)} - \sin\theta_0 \end{cases}, \quad t \in \left(\frac{\pi}{2} + \theta_0, \frac{3\pi}{2} - 3\theta_0\right) \end{cases} \qquad \text{(eq. 1)}$$

where θ_0 is the half-acceptance angle of the CPCs and t the parameter that allows plotting the profiles.

Originally, the Tolokatsin design consisted of eight mirrors, distributed in four pairs, as shown in Fig. 2(a) and Fig. 2(b). The designs work properly for cooking at 140 ºC, however, during its continuous operation for more than 10 years, it was noted that the optical performance of the system can be increased, keeping the same concentration ratio (2.75x), with less use of mirror and decreasing the optical leakage by using 2 more mirrors, as shown in Fig. 2(c). This was also independently investigated by (Cooper et al., 2013a), where it is shown that the square aperture has some favorable anomalous behavior, validating the use of the 1-dimensional curvature mirrors for a 3D design; although this analysis was for a single-stage concentration system.



(a) Sketch of the original design

(b) Original Tolokatsin **(c) Tolokatsin-V**

Fig. 2: Tolokatsin first improvements

2.1. Further improvement of the Tolokatsin solar ovens with the constructal law

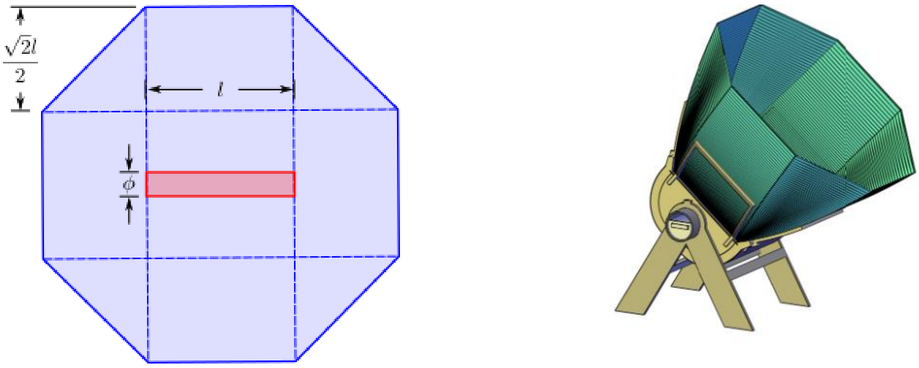
Although all the improvements mentioned above have been the result of the continuous use, Gonzalez-Mora et al. (2020) recently demonstrated that with the use of Bejan's constructal law (Bejan and Lorente, 2008; Rocha et al., 2012), it is possible to obtain the same results that were found experimentally, considering that:

"For a finite-size system to persist in time (to live), it must evolve in such a way that it provides easier access to the imposed (global) currents that flow through it."

The results of the constructal law applied to the Tolokatsin solar cooker concept led to the following conclusions:

- increase the optical efficiency of the concentrator by reducing the average number of reflections of rays that imping on the absorber
- increase the concentration ratio (and so the stagnation temperature of the absorber)
- improve thermal insulation.

By allowing the design to continue to evolve, in such a way that the concentrated solar radiation passing through the optics of the system reaches the receiver (González-Mora, 2021), it is shown that by increasing the number of mirrors (originally one pair of top mirrors, then two pairs and finally three pairs), it is possible to redirect the sunlight in a better way by decreasing the average number of reflections; and also to obtain a more homogeneous radiation flux over the absorber, even for the combination of single curvature CPCs, as shown in Fig. 3.



a) Aperture area **(b) 3D isometric view**

Fig. 3: Tolokatsin-2020 design

3. Optical analysis

While performing the constructal analysis (González-Mora et al., 2020), it was possible not only to validate the truncation criterion that was proposed from a geometrical perspective by Rincón et al. (Rincón Mejía et al., 2009) but also, thermodynamically, by capturing the same amount of energy as a system without truncation; where this energy is given by a relation of the type $Q \sim G_b\, C_g\, \eta_o$, where the geometrical concentration $C_g = C_g(\theta)$, and also considering that the optical efficiency is a parameter that depends directly on the average number of reflections N in the optical system by means of a relation $\eta_o \sim \rho^N$.

Originally, the average number of reflections for 2D CPC's without truncation was studied by Rabl (Rabl, 1976), and in (González-Mora et al., 2020) the corresponding analysis have been obtained for the system with truncation, which we can be recalled as an "optimal" value. This analysis has even shown that truncation not only allows a reduction of the mirror quantity, but also the average number of reflections N decreases considerably because this parameter depends directly on the geometrical concentration and the acceptance angle $N = N(C_g, \theta)$. Since no formal optical analysis had been performed for the Tolokatsin solar cookers, there was an urgency to do a ray-tracing procedure, which can validate the results and even, identify future optimizations via the constructal law (González-Mora, 2021).

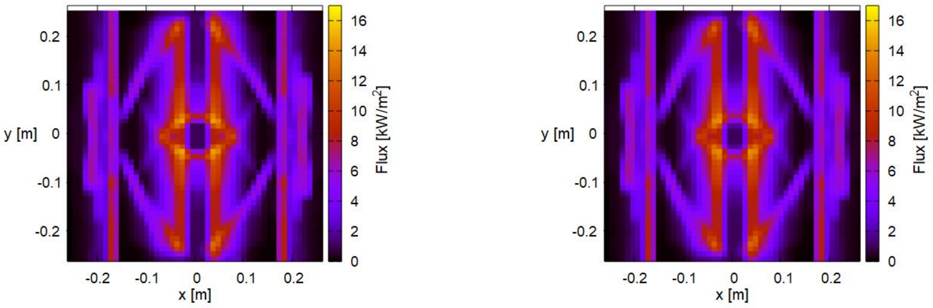
3.1. Analysis of the Tolokatsin 2020

The Tolokatsin-2020 has a concentration ratio of 5.8x, with a 16.86 cm receiver diameter, and an aperture area of 1.621 m^2. For the optical evaluation of the new design, a Monte-Carlo ray-tracing scripting procedure was performed in SolTRACE (Wendelin, 2003) with the use of Zernike Polynomials (Doyle et al., 2012) (Eq. 3) to define the surfaces, where $B_{i,j}$ are the coefficients and N the polynomial degree. As data input, the following parameters were considered:

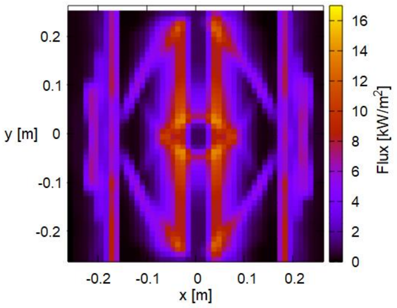
- 0° incidence angle
- The radiation source was modeled as isotopic with 4.65 mrad (pillbox sun shape) and a Gaussian profile with 2.73 mrad
- 0.92 mirror-reflectivity
- 0.94 receiver-absorptivity
- 0.98 glass covers transmissivity
- 3 mrad slope error for the mirrors and 1.95 mrad for the receiver
- 0.5 mrad specularity error
- 1000 W/m^2 DNI

$$z(x,y) = \sum_{i=0}^{N} \sum_{j=0}^{i} B_{i,j} x^j y^{i-j} \quad \text{(eq. 3)}$$

For the optical simulation, three cases are considered: 1) no optical errors, 2) optical errors and pillbox solar distribution, and 3) optical errors and Gaussian distribution. Each flux map is shown fin Fig. 4. The first case was used to define the peak optical efficiency, while the other two cases the variation of the optical efficiency under construction errors for a more accurate behavior of the real system. In the three cases, similar behavior is noticed even for including/excluding the optical errors and for different sun-shape.



a) Case 1 **(b) Case 2**



(c) Case 3

Fig. 4: Tolokatsin-2020 design

The optical efficiency (Eq. 4) is quantified as the ratio of the heat flux reaching the absorber ($\dot{Q}'_{rec}$) to the heat flux entering the aperture of the Tolokatsin-2020 ($\dot{Q}'_{ap}$). Table 1 summarizes the results of the optical analysis of each case.

$$\eta_o = \frac{\dot{Q}'_{rec}}{\dot{Q}'_{ap}} \quad \text{(eq. 4)}$$

where each heat flux is computed as a function of the number of rays impinging the surfaces and the power per ray. In each case, 10 million rays were used for the analysis; the same number of rays was used by Cooper et al. (2013), enough to obtain an uncertainty of the order of 0.01%.

The similar behavior and optical efficiency of the three cases can be explained by the incompressibility of the sun rays across the optical path in the non-imaging optics system as stated by Fermat's principle and the etendue conservation (Winston et al., 2020).

Tab. 1: Results of the optical analysis

Parameter	Case 1 (no errors)	Case 2 (pillbox)	Case 3 (Gaussian)
Average flux [W/m2]	3436.32	3434.21	3435.44
Peak flux [W/m2]	17839	16392.9	16372.7
Optical efficiency [%]	81.09	81.03	81.02

3.2. Comparison with the Tolokatsin-V

As shown in Fig. 2(b) and Fig. 2(c), the original Tolokatsin design and the Tolokatsin-V have a square-shaped aperture area, while the Tolokatsin-2020 (Fig. 3) has an octagonal shape. To compare the advantage of adding more mirrors, a raytracing of a modified version of the original design and the Tolokatsin-V was performed with the same concentration ratio (5.8X). The heat fluxes on the receiver are displayed in Fig. 5.

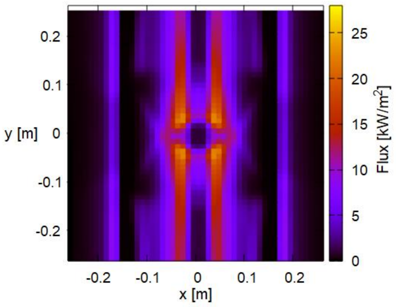


Fig. 5: Tolokatsin-V flux map on the receiver

Comparing Figs. 4 and 5, the Tolokatsin-V receptor has a higher radiation peak than the Tolokatsin-2020; however, the flow is less uniform and covers a smaller area. Whit these results, an important result must be addressed, since until now, the use of a collimator inside a concentrating solar cooker was unaware of the main solar-cookers users and designers, since the use of concentrating devices leads to a higher temperature and a time-reduction for cooking is well understood and implemented, so the use of a collimator, which inherently decreases the concentration ratio, seems to be contradictory. However, the underlying objective of including a collimator in the lower part of the design lies in a “trap” for all the photons in a finite-sized zone wrapping the receiver, which is invariant to the sun shape, as can be seen in the flux maps of Fig. 4.

As described previously, the optical efficiency for the Tolokatsin V was quantified at 74.3%. Comparing the results from Table 1 with this design, it can be noticed that the Tolokatsin-2020 increased its optical performance by 9.14%. The improvement of the optical behavior is justified by a considerable reduction in the number of reflections of the sun-light to reach the absorber, as predicted previously with the use of the constructal law (González-Mora et al., 2020), and a better flux distribution on the receiver.

4. Conclusions

It can be seen from the results, that to guarantee excellent performance and great reliability is recommended the systematic application of the constructal theory, as demonstrated easily by González-Mora et al. (2020), and validated with the +25 years of continuous operation and some improvements of the Tolokatsin designs; however, until now, no formal optical analysis over the Tolokatsin designs was performed.

The optical efficiency of the Tolokatsin designs has been determined, where it is demonstrated that the increase in the number of upper-mirrors, led to an increase of the efficiency, from 74.3% of the Tolokatsin-V to 81% in the Tolokatsin-2020. However, a drawback must be noticed since the new sophisticated design has a greater manufacturing complexity and costs.

The 9.4% optical efficiency increase can be explained by the use of a collimator in the lower part of the system, and the reduction of the number of reflections, resulting in better flux patter onto the receiver. The collimator generates a “photon trap”, where all the light reaching the collimator’s aperture is finally redirected to the absorber. The reduction of the number of reflections was achieved with the “optimal” truncation criterion, as demonstrated in previous work (González-Mora et al., 2020), and validated with the ray-tracing procedure.

With the optical analysis been performed, a formal thermal analysis can be done in future works to quantify the figures of merit F_1 and F_2, and the standardized power. This would lead to a full characterization of the Tolokatsin-2020 design, and with further constructal analysis, the possibility of identifying new opportunities to improve the solar energy transfer to the receiver and cook in a better way.

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