Energy and Entropy Characterization of the Tolokatzin Solar Collector Designs for Multiple Applications

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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 "Tolokatzin" (Náhuatl language name meaning "born in Toluca", the city in which they were created) were designed. Nowadays, the Tolokatzin 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. After 20 years of successful experience in its operation, its application has evolved to be able to be applied as a solar sterilizer and other applications that require different temperatures and flux densities than those necessary for cooking. A further advance has been made to reduce the losses by reflections, by changing the number of mirrors and the solar concentration, keeping only mirrors of simple curvature (very easy to manufacture). With this background, in the present paper, an energy and entropy characterization are done for the different configurations that integrate the Tolokatzin designs.

Keywords: Tolokatzin; solar oven; non-imaging optics; energy; entropy

1. Introduction

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, 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.

It has been wide studied and reported by members of the Solar Cookers International (SCI, 2019) many alternatives to use solar stoves and ovens to cook safely for all people, 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. Taking this into consideration, the Tolokatzin solar ovens (meaning "born in Toluca" – the city in which they are from – in Náhuatl language) were designed and built more than 20 years ago.

The main difference of the Tolokatzin 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 (absorber), resulting in a compact multi-compound system that can achieve high temperatures in few time (González-Mora and Rincón-Mejía, 2018a; Winston et al., 2005). The direct application of non-imaging optics allowed the applications of Tolokatzin to be extended to other sectors as solar sterilizing, diversifying the original line of its design.

Among the applications in which the Tolokatzin designs have ventured successfully, apart from solar cooking, water-free solar sterilization and wastewater treatment stand out (González-Mora and Rincón-Mejía, 2018b, 2018c; González Mora et al., 2016). Even though the applications of the original Tolokatzin have diversified, the

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concept remains the same: "Optically and thermally optimized systems that allow the best performance even in climates that are not so favored with the sun, capturing direct radiation and a great portion of the diffuse radiation, using multi-compound systems with simple curvature mirrors two-dimensional that operate under the principle of three-dimensional concentration". This should be interpreted as the use of optimally truncated CPCs with a circular, square or flat receiver to maximize operating time, concentrated irradiance and the use of materials.

With the aforementioned background, the energy and entropy characterization are developed under the considerations:

- The three heat transfer mechanisms are modeled
- The Parrot model of entropy (Petela, 2010) is applied to each Tolokatzin design

2. Origins of the Tolokatzin solar ovens

The first Tolokatzin design was originally developed to cook, however, while trying to use non-imaging optics the prototypes faced several restrictions, as:

- It must heat up to 140 °C, high enough to cook, but not too high to burn the meals
- It doesn't need to follow the sun while the meals are prepared
- It must be safe and easy to use
- Preferably it must be manufactured with no complication at home
- It must be an attractive design, light and portable

2.1. Evolution of the opto-geometric description based on the design criteria

In order to get a functional CPC, it must be truncated to reduce its height, this is naturally important for economic reasons in large-scale applications, however, as in any engineering application, cost reduction is important without compromising device performance to a greater extent (O'Gallagher, 2008; Rabl et al., 1979). Within the various truncation criteria, the truncation according to the Rincón's criterion establishes that any CPC must be truncated in such a way that rays parallel to the extreme rays are not blocked by the mirrors of the CPC [3]. As shown in Fig. 1, the Rincón's criterion reduces considerably the height with no reduction of the concentration ratio.

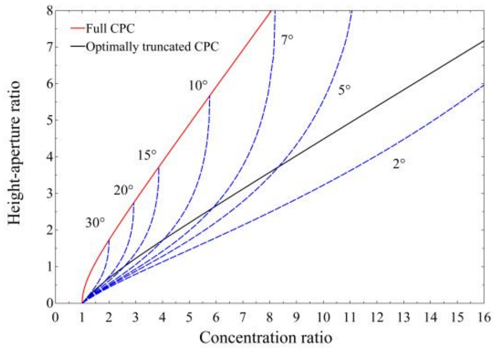
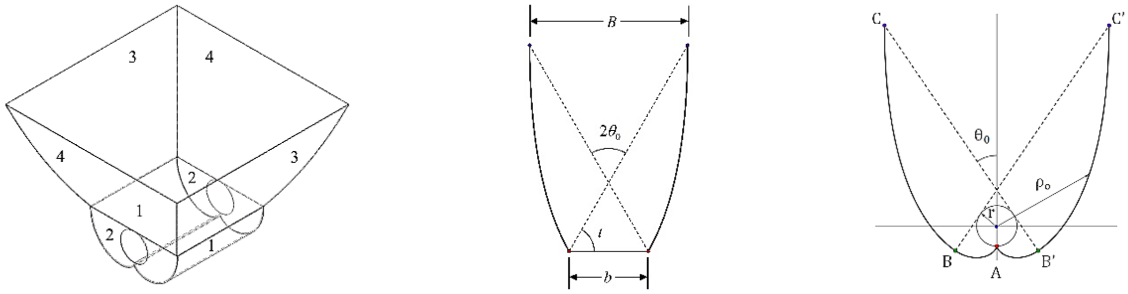


Fig. 1: Ratio of height to aperture for full and truncated CPCs.

This optimization not only leads to a considerable reduction in height. This optimization also allowed to obtain an adequate solar radiation flow over the absorber. This should be understood as a proper design criterion from the optical and thermal point of view, in concordance with the constructal law (Bejan, 2016).

3. The Tolokatzin Solar Oven

The Tolokatzin solar oven is a non-imaging optics multi-compound solar concentrator (CMC) with 8 mirrors, distributed in four pairs as shown in Fig. 2 (a). As a non-imaging optics concentrator, it uses a combination of 2D cross-compound parabolic collectors (CPCs) for flat (Fig. 2 (b)) and circular absorber (Fig. 2 (c)); in this way, a 3D concentration device is obtained from generating simple curvature mirrors.



(a) **(b)** **(c)**

Fig. 2: Geometry of theTolokatzin with a CPC with flat absorber and circular absorber.

3.1. Optogeometric description of the Tolokatzin solar oven

The geometry that allows describing the CPC is not simple, however, after more than 50 years (O'Gallagher, 2008; Winston et al., 2005), the curves have diversified and adapted for easy understanding. Since the Tolokatzin solar oven employs both CPCs with a circular absorber and a flat absorber, both geometries are described below.

3.2. CPC with flat absorber

The geometry for the CPC with flat absorber has been the most discussed, and we will not address a bibliographic review of it; however, this geometry corresponds to two arches of parabola rotated respect to the vertical. This rotation is what defines the half-acceptance angle θ_0. The parametric curves for this CPC (Fig. 2 (a)) are:

$$\begin{cases} x(t) = \frac{b(1+\sin\theta_0)\cos t}{1-\sin(t-\theta_0)} \\ y(t) = \frac{b(1+\sin\theta_0)\sin t}{1-\sin(t-\theta_0)} \end{cases} \qquad \text{(eq. 1)}$$

3.3. CPC with circular absorber

Unlike the CPC with flat absorber, the CPC with a circular absorber is formed by 2 pairs of curves called involutes (AB in Fig. 2(c)) and anti-caustics (BC in Fig. 2(c)). Thereof which also defines the half-acceptance angle θ_0. The parametric curves for this CPC are:

$$AB\colon \begin{cases} x(t) = a(\sin t - t\cos t) \\ y(t) = -a(\cos t + t\sin t) \end{cases} \qquad \text{(eq. 2)}$$

$$BC\colon \begin{cases} x(t) = a\left[\frac{\sin\theta_0\cos(t-\theta_0)-\left(\frac{\pi}{2}+t+\theta_0\right)\cos t}{1+\sin(t-\theta_0)} + \cos\theta_0\right] \\ y(t) = -a\left[\frac{\cos\theta_0\cos(t-\theta_0)+\left(\frac{\pi}{2}+t+\theta_0\right)\sin t}{1+\sin(t-\theta_0)} - \sin\theta_0\right] \end{cases} \qquad \text{(eq. 3)}$$

3.4. Combination of the CPCs with flat and circular absorber for the Tolokatzin solar oven

As can be seen in Fig. 2 (a), the CPC with a flat absorber is placed on top of the CPC with the circular absorber. Since a restriction on the operating temperature has been set, the geometric concentration coefficient of the entire device is 4; with the consideration that the CPC with circular absorber is of unitary concentration; and that the CPC with flat absorber has a concentration of 2, and since it is a three-dimensional geometry, the total concentration of 4 is finally obtained.

Since the two geometries of the CPC are working as if it were a concentration in two stages. Note also that the design uses only simple curvature mirrors that, when coupled together, achieve three-dimensional geometry. This feature of the Tolokatzin solar ovens, allowing easy manufacturing for prompt operation.

4. Thermal analysis of the Tolokatzin solar oven

The thermal model is based on energy balances at each element involved in the cavity of the lower CPC, as shown in Fig. 3; however, the geometries involved are not so simple to determine each heat flux. A detailed description of the heat fluxes can be found in Veynand (2011), Montes Pita et al. (2016) and Prapas et al. (1987).

The surfaces are identified as: (1) inside fluid, (2) inner wall of the absorber, (3) outer wall of the absorber, (4) CPC mirrors, (5) inner insulation, (6) outer insulation, (7) inner surface of the window surface, (8) outer surface of the window surface, (9) external environment.

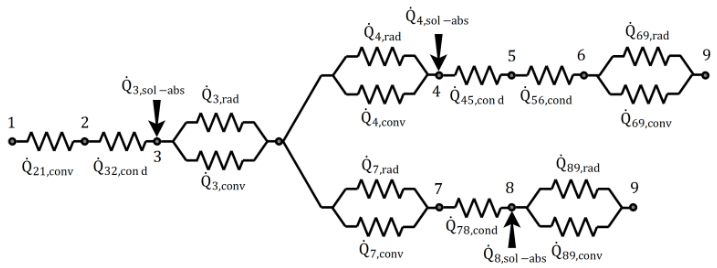


Fig. 3: Thermal resistance model of the CPC with the subscript that identify each surface.

The thermal model consists of 29 equations and 29 unknowns that are grouped into 7 final equations, which involve 7 well-defined groups:

- Group 1: 3 solar absorptive equations to calculate ($\dot{Q}_{3,sol-abs}$, $\dot{Q}_{4,sol-abs}$, $\dot{Q}_{8,sol-abs}$)
- Group 2: 4 conduction equations ($\dot{Q}_{32,cond}$, $\dot{Q}_{45,cond}$, $\dot{Q}_{56,cond}$, $\dot{Q}_{78,cond}$)
- Group 3: 6 convection equations ($\dot{Q}_{21,conv}$, $\dot{Q}_{3,conv}$, $\dot{Q}_{4,conv}$, $\dot{Q}_{69,conv}$, $\dot{Q}_{7,conv}$, $\dot{Q}_{89,conv}$)
- Group 4: 5 radiation equations ($\dot{Q}_{3,rad}$, $\dot{Q}_{4,rad}$, $\dot{Q}_{69,rad}$, $\dot{Q}_{7,rad}$, $\dot{Q}_{89,rad}$)
- Group 5: 2 radiosity equations
- Group 6: 9 balances, one per node from 2 to 8 plus the central one of the cavity

Once the model has been solved it is possible to establish a graph of the temperature increase in the inner wall of the receiver as a function of time, (Fig. 4). Analysing the graph, it can be seen that the temperature is practically the same throughout the year.

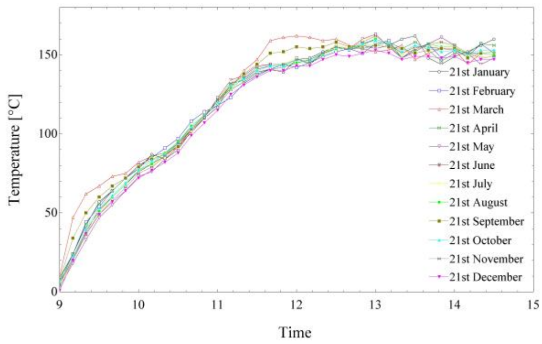


Fig. 4: Receiver temperature over the year.

With the diagram shown in Fig. 3, the surface temperatures and heat fluxes can be related and can be estimated. A good estimator for the performance of a concentrating device is the entropy generated, the optimum collector temperature and the stagnation temperature (Kalogirou, 2014). According to the graph plotted in Fig 5, the stagnation temperature for a 4x concentrator is $560\ K$, and the optimum receiver temperature is $401\ K$, with a non-dimensional entropy generation of $0{,}69$.

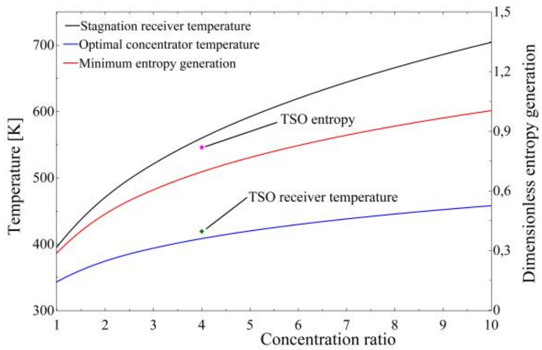


Fig. 5: Entropy generated and optimum temperatures against collector concentration ratio.

For the new Tolokatzin models, the receiver average temperature is near the $420\ K$ with a non-dimensional entropy generation of $0{,}82$. These values are not so far from optimal.

5. Conclusions

As can be seen in Fig. 1, the truncation of a CPC decreases significantly in height, however, by making an optimal truncation under the Rincón's criterion, there is no reduction in concentration as with another truncation criterion. Thus, for the design of the Tolokatzin, the height has been reduced by just over half, which makes the solar oven a more compact device easier to operate and transport.

From Fig. 4, it can be seen with clarity that the temperature in the internal part of the receiver is practically the same throughout the year. This means that the Tolokatzin solar oven will be working very similarly during the year regardless of the day of use, under the reservation of cloudy or rainy days.

The most important result derived from this brief analysis is shown in Fig. 5. There, it is clear that the temperature of the receiver is very close to the optimum theoretical value, in such a way that, the flow of heat through the CPC has been optimized using a properly truncation, resulting in a generation of entropy that is too close to the minimum value, which translates as a device that allows an efficient energy transformation.

References

Bejan, A., 2016. Advanced Engineering Thermodynamics, 1st ed, John Wiley & Sons. Wiley, New Jersey.

González-Mora, E., Rincón-Mejía, E.A., 2018a. Conceptos básicos de la concentración solar. Notas de clase. FI-UAEM.

González-Mora, E., Rincón-Mejía, E.A., 2018b. ANÁLISIS 2E DE UN SISTEMA SOLAR PARA TRATAMIENTO DE AGUAS EMPLEANDO ÓPTICA ANIDÓLICA, in: XVI Congreso Ibérico y XII Congreso Iberoamericano de Energía Solar. Madrid.

González-Mora, E., Rincón-Mejía, E.A., 2018c. Design and environmental impact assessment of an improved CPC for Solar-Photo-Fenton., in: International Conference on the Management of Energy, Climate and Air for a Sustainable Society. La Habana.

González Mora, E., Rincón Mejía, E.A., Moreno Lawrence, D., 2016. USING A NEW SOLAR STERILIZER FOR SURGICAL INSTRUMENTS AS A SOLAR OVEN FOR COOKING, in: VIII Congresso Ibérico | VI Congresso Ibero-Americano Das Ciências e Técnicas Do Frio. Coimbra, pp. 3–6.

IEA. International Energy Agency, 2018. World Energy Outlook 2018 [WWW Document]. URL https://www.iea.org (accessed 2.24.19).

Kalogirou, S.A., 2014. Solar energy engineering : processes and systems, 2nd ed. Elsevier.

Lecuona, A., I. Nogueira, J., Rodríguez Aumente, P., Legrand, M., 2017. Solar Cooking for All, in: Rincón-Mejía, E., De las Heras, A. (Eds.), Sustainable Energy Technologies. CRC Press, pp. 255–276.

Montes, M.J., Barbero, R., Abbas, R., Rovira, A., 2016. Performance model and thermal comparison of different alternatives for the Fresnel single-tube receiver. Appl. Therm. Eng. 104, 162–175. https://doi.org/10.1016/j.applthermaleng.2016.05.015

O'Gallagher, J., 2008. Nonimaging Optics in Solar Energy, 1st ed, Synthesis Lectures on Energy and the Environment: Technology, Science, and Society. Morgan & Claypool Publishers.

Petela, R., 2010. Engineering Thermodynamics of Thermal Radioation For Solar Power Utilization, 1st ed. McGraw Hill, New York. https://doi.org/10.1017/CBO9781107415324.004

Prapas, D.E., Norton, B., Melidis, P.E., Probert, S.D., 1987. Convective heat transfers within air spaces of compound parabolic concentrating solar-energy collectors. Appl. Energy 28, 123–135. https://doi.org/10.1016/0306-2619(87)90046-8

Rabl, A., Goodman, N.B., Winston, R., 1979. Practical design considerations for CPC solar collectors. Sol. Energy 22, 373–381. https://doi.org/10.1016/0038-092X(79)90192-0

Rincón Mejía, E.A., 2010. Aplicaciones de la óptica anidólica en concentradores solares.

SCI, 2019. Solar Cookers International [WWW Document]. URL https://www.solarcookers.org/ (accessed 2.24.19).

Veynandt, F., 2011. Cogénération héliothermodynamique avec concentrateur linéaire de Fresnel : modélisation de l'ensemble du procédé. Université de Tolouse.

Winston, R., Miñano, J., Benítez, P., 2005. Nonimaging optics, 1st ed. Elsevier, New Jersey.