Nonimaging Optics and Constructal Design Towards Optimal Solar Cookers

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Abstract

According to the WHO nowadays all over the world millions of people get sick and die each year from inhaling the fumes produced by the combustion of wood and other fuels for cooking, causing much more deaths than the those due to COVID-19! These deaths and illnesses can be significantly reduced by using very efficient, reliable, safe and economical solar cookers with which any type of food could be cooked most of the days of the year. Even thought there are today lots of succesfull designs of solar cookers, we still need such optimised designs that could operate even in frankly cloudy days; the solar cookers presented here meet these strict requirements. Globally, cooking food involves a significant and unavoidable consumption of energy cause more than 7.8 billion people must eat at least three times a day and this cooking is done mostly by burning fossil fuels or firewood, generating a large amount of toxic and greenhouse gases and particles that are very harmful to health and the environment. The massive use of solar cookers would have great benefits, but to guarantee their use for at least 85% of the days of each year it is necessary to have very high-performance solar cookers, keeping ease use and reasonably low manufacturing costs. The use of Nonimaging Optics and the Constructal Design have made possible to create solar cookers with which them is possible to cook any food on almost any day of the year. Details of their design and some operational results are sumarised here.

Keywords: Nonimaging Optics, Constructal Design, Solar Cookers

Introduction

According to the World Health Organization (WHO, 2018), the combined effects of ambient (outdoor) and household air pollution -mainly due to fumes produced by the combustion of fuels for cooking- cause about seven million premature deaths every year, mostly as a result of a great mortality from strokes, heart diseases, chronic obstructive pulmonary disease, acute respiratory infections and lung cancer. The WHO also estimates that there are globally 3.8 million deaths per year attributable just to household air pollution. This figure corresponds to nearly double of deaths due to COVID-19 during the first year of the pandemic! The estimate is based on the strength of the evidence, primarily meta-analyses of epidemiologic studies of acceptable scientific quality, although for cardiovascular disease, the evidence is more inferential (Balmes, 2019). As a matter of fact, air pollution poses a major threat to health and climate that causes deseases and mortality all over the world (Kumar and Mehta, 2016; Boogaard et al. 2017; Rosenthal et al. 2018; Conibear et al. 2020).

For millennia humanity based its cooking on the combustion of biomasses. Even nowadays, about a third of the world's population continues to burn firewood because to their poverty they do not have access to fossil gas or electricity. Besides the foregoing, collecting firewood carries risks for women and children, along with a loss of time for living. Furthermore, fuelwood consumption in impoverished regions contributes to deforestation: according to Bailis et al. (2015), “over half of all wood harvested worldwide is used as fuel, supplying ~9% of global primary energy. By depleting stocks of woody biomass, unsustainable harvesting can contribute to forest degradation, deforestation and climate change. Approximately 275 million people live in woodfuel depletion hotspots -concentrated in S. Asia and Africa- where most demand is unsustainable”.

On the other hand, in urban areas almost the entire population burn fossil gas or use electricity for cooking. As it is well known, the consume of gas causes much of the indoor air pollution and other hazards, such as burns, explosions and poisonings. Hundreds people annually suffer accidents directly or indirectly related to gas consumption. Besides all that, cooking with gas or firewood favors the production of toxic or carcinogenic substances in food, especially when exposed to high temperatures, which also degrade nutrients and can burn or char them when they are not attended to during cooking.

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Our ASES SOLAR2020 Conference is held within the framework of the most serious global pandemic that humanity has suffered in more than a century, which has caused enormous mortality in countries that have populations with high rates of obesity, malnutrition, diabetes, hypertension and other maladies derived mainly from a poor diet based on industrially ultra-processed foods, with a lack of nutrients and an excess of preservatives, flavorings, colorants, sweeteners, and other chemical substances recognized to be addictive, toxic, carcinogenic and favoring obesity and hypertension. In addition to these harmful substances added purposefully to food, there are others that are formed when food is processed using too high temperatures, such as acrylamide and furans amongst many others. The second comorbidity factor that aggravates COVID-19 is chronic respiratory diseases caused by combustion fumes generated in cooking food, internal combustion engines, smoking, fires and other sources of toxic gases. The foregoing shows that, as a priority public health issue, we must change the way we eat as soon as possible, from the production of food, its processing to final consumption. Solar food processing, which includes the essential cooking of some meals to make them edible (such as legumes, tubers, meats, herbs) offers an excellent opportunity to remedy many of the serious problems that we face. In particular, solar cooking of food offers the following great benefits:

1.- Reduces exposure to fumes from the combustion of firewood (or LPG, methane or other fuels) that cause respiratory diseases in millions of people.

2.- It contributes to achieving food and energy sovereignty, and to reducing poverty (Sun rises for free for everyone!) by dispensing with the need to consume fuel or electricity through inefficient and expensive supply chains.

3.- In addition to helping to care for the environment by avoiding deforestation, cooking and pasteurization of water with solar energy reduce the emission of GHG and the formation of dangerous substances that begin to form inside food when the cooking temperature exceeds 120°C.

4.- Solar cooking conserves the nutrients quality and offers a much better flavor.

5.- Besides all the above, solar cooking contributes significantly to achieving the 17 Sustainable Development Goals (SDGs) of the United Nations 2030 Agenda to face climate change, which today, after COVID-19, it is the second most important issue in the UNO's agenda. As a matter of fact, without solar cooking the SDGs could not ever be achieved.

Solar Cookers

Solar cookers are not a novelty in themselves, they have been working for centuries. However, nowadays they still are a real discovery for many, because of the curiosity they represent and the disbelief about their possibilities. "Except for smoked, there is no culinary process that is not possible with them, nor size that escapes them. However, their use is not generalized, although in the world they are counted by millions" (Lecuona, 2017). They are a great resource in the fight against energy shortages, and although commonly they are not able to satisfy 100% daily needs, on very cloudy or rainy days, conventional means can be used; after all, every good restaurant -and even many dwellings- have several complementary devices to cook any dish at any time! Solar cookers can indeed cleanly supply most of the domestic energy consume in many sunny countries.

There are many types and variants of solar cookers, depending on their application, operating life, cost, size, with the possibility of being built in-situ, etc. (Nandwani, 2004; Lecuona, 2017; Kundapur, 2018). Figure 1 shows the four most successful types, adapted to their use: fast and slow, and the advanced non-imaging type.

All efficient solar cooker has a cavity within which one or more vessels containing the food to be cooked are placed. This cavity is heated by solar radiation, preferentially concentrated by the use of mirrors, that enters it through a transparent cover. The cavity is thermally insulated from the exterior using the most suitable materials. Radiation losses are commonly reduced by using selective coatings.

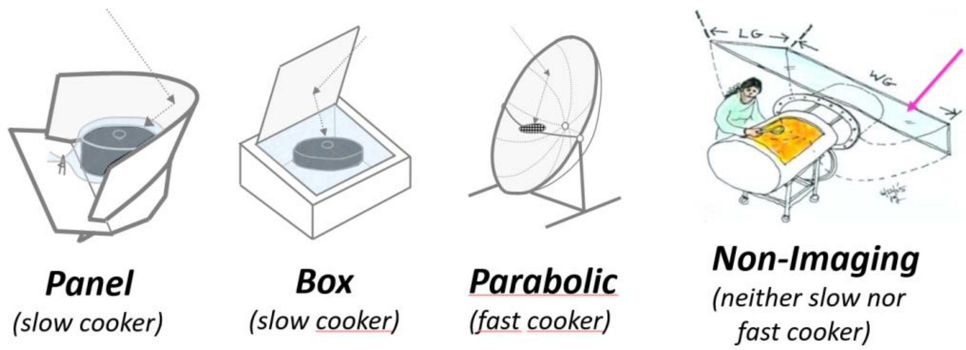


Fig. 1: Four common types of solar cookers (Drawings courtesy of Professor Celestino Ruivo and Architect Joel Goodman)

In order to reach out temperatures high enough to fry and reduce cooking times, solar concentration has often been used, but reaching excessively high temperatures leads to a degradation of nutrients, a generation of toxic products and, due to the increase of thermal loses, to a reduction of its thermal efficiency. That is why it is a key point to design the solar cooker to reach not less, but not much more either, of the required temperature for the adequate cooking process; this is easy to be realised with the aid of nonimaging optics.

Nonimaging Optics

The matter of classical optics has been to resolve problems such as the designing imaging-forming optical systems of a very large aperture. Its applications include devices such as telescopes, microscopes, radiometers, variable focus lenses, etcetera. It is based on theory of electromagnetic waves and includes Snell's law of refraction and the phenomena of diffraction, interference, and even the photoelectric effect (Smith, 1966). By contrast, in nonimaging optics - developed just over half a century ago by Roland Winston, the then Soviet V. K. Baranov and G. K. Melnikov, as well as the German M. Ploke, among others - the underlying idea is, rather than forming images of the light source in a focal zone, it is desired to catch photons in a finite-sized zone, even if the "image" formed there has huge aberrations and is fragmented. For solar concentrators, like the ones used in our nonimagings solar ovens, that is very convenient cause nonimaging solar concentrators are much more efficient that the image-forming concentrators (Winston et al., 2005). Instead of pretending concentrate the sun light in punctual (or linear) focuses, light is conducted through mirrors and/or lenses to a finite region of many possibles geometries wraping the so called "absorber" of the concentrator. However, it must be recalled that: "imaging and nonimaging are not opposite concepts. Only if we restrict ourselves to a finite number of elements can perfect concentrators with plane apertures and axial symmetry not be obtained" (Winston et al., 2021).

3.1 The Compound Parabolic Concentrators

The solar concentrator with a flat absorber was the first to be discovered and were called "Compound Parabolic Concentrator" or CPC because it is formed, for the two-dimensional (2D) case, by two cylindric mirrors of parabolic section, as it is shown in figure 2. Point B is indeed the linear focus of the cylindric-parabolic segment CD, while C is the corresponding linear focus of parabolic segment AB. For mirrors hypotetical perfect, all rays ingresing the aperture area AD with an inclination -with respect to the CPC's axis- lesser than the acceptation half angle θo would be reflected towards the absorber BC after impinging on one of the mirrors; of course, some rays can go directly to the absorber without any reflection. In this case, the non-truncated CPC has a geometric concentration $C_{g\,2D} = \frac{|AD|}{|BC|} = 1/\sin(\theta o)$, and for the 3D case, the geometric concentration is $C_{g\,3D} = [|AD|/|BC|]^2 = 1/sin^2(\theta o)$. As the temperature that is posible to reach out with a solar concentrator dependends mainly on C_g, the advantage of using a 3D concentration becomes evident.

The foregoing geometry geometry is ideal for applications where the absorber is naturally flat, as in PV systems, but is not quite good for applications like the heating of fluids, where clearly the more adequate geometry for the absorber is a cylinder of circular cross-section. Figure 3 shows a CPC-type 2D concentrator for this kind of absorber. Mirrors AE and FD are no longer parabolic, even though the "CPC" name remains. The Tolokatsin solar ovens takes advantage of this two CPC geometries as it is explained in next sections.

The main disadvantage of CPCs occurs when the acceptance angles are relatively small: the length of the mirrors becomes excessively large and there is a need to truncate them. The optimal truncation is obtained when most of the area of the mirrors is truncated and even so the consequent decrease in concentration does not prevent reaching out the required temperatures and radiative fluxes. However, that optimum condition depends on the variable proportions of diffuse and beam radiation present in a given instant. A criterion for an optimal truncation that is independent of the conditions of radiation is stated in the following section.

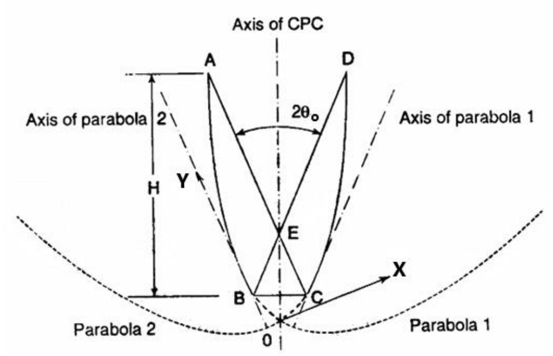


Fig. 2: The Compound Parabolic Concentrator for an flat absorber. It was the first nonimaging concentrator

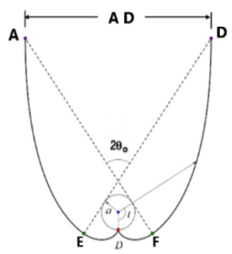


Fig. 3: The Compound Parabolic Concentrator for a circular absorber

3.2 Truncation of CPC mirrors according to Rincón's Criterion

Rincón's criterion states that: "the CPC must be truncated in such a way that rays parallel to the extreme rays (AC and BC in figure 3) are not blocked by the mirrors of the CPC" (Rincón et al., 2009). Observing figure 3, this implies that straight line QT, which is tangent to the parabolic mirror CD at point T, must be parallel to the extreme ray BD. That occurs, independently of the shape of the absorber -assuming that its surface in uniformly convex or plane- when the truncation angle t_t is $t_t = \pi/2 - 3\,\theta_0$, where $\theta_0 < \pi/6$. With this procedure, the angular window for the acceptation of difusse irradiance increases from $2\theta_0$ for the non-truncated CPCs, to $6\theta_0$ for the optimally truncated ones. This criterion is used in all the nonimaging concentrators of the Tolokatsin solar cookers.

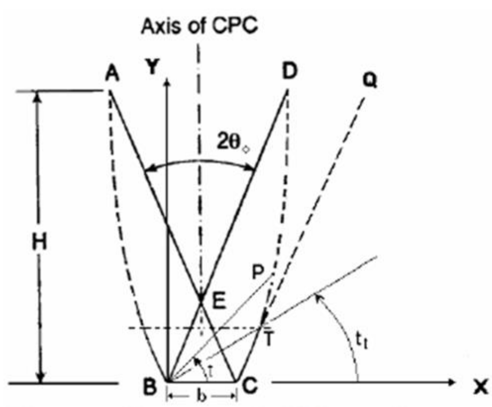


Fig. 4: Truncation of a CPC for a plane absorber according to Rincón's Criterion

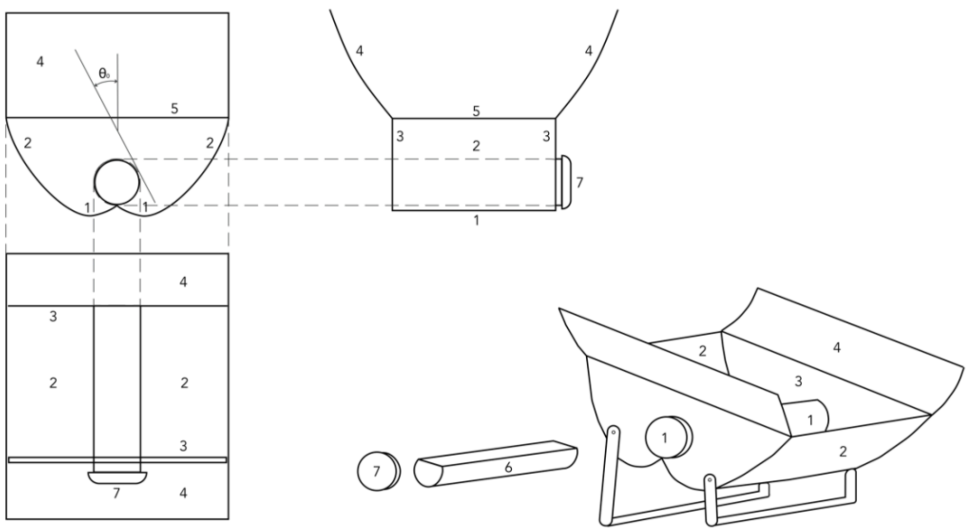
The Tolokatsin Solar Ovens

In 1995 the first “Tolokatsin” solar cooker was designed (Rincón et al., 1997) with which it was possible to cook any food on almost every day of the year. *Tolokatsin* is a Mexica Nahuatl word meaning “dear girl born in Toluca”, cause in that city they were designed for the first time. It was based on anidolic optics, and the original design consisted of a Multi Compound Concentrator (MCC) with exactly eight mirrors, distributed in four pairs, as it is shown in figure 5.

The essential point of these MCCs is that they achieve a 3D concentration from mirrors of simple curvature, truncated according to Rincón's Criterion. This makes them very easy to manufacture, even in locations far from industrial zones. The absorbers of the MCCs are cylindrical containers that can be hermetically closed which are heated by the concentrated sunlight reflected by the mirrors. Inside the cylindrical absorbers, at least one food grade stainless steel tray is placed in which the food is placed as shown in figure 6. Depending on the size of the containers, one, two ore more trays can be placed inside them. No meal can be burn, since the temperature inside the ovens commonly does not exceed 140°C.

With a hermetic closure the ovens work pressurized, but their containers were designed to resist presures one order of magnitude greater than the maximum working pressure attainable with the solar concentrator, so no need of valves nor pressure regulators for a quite safe operation. In more than 25 years of operation of a few thousands of these cookers, no incidents or accidents have been reported.

Thanks to their hermetic closures and that they operate at temperatures at which no bacteria or viruses can survive, as long as the containers are not opened, once the food is cooked they could be kept for days without the need for refrigeration (this is not recommended of course). Food can be placed in the oven even before dawn, and taken out whenever it is desired to eat (noon, afternoon, evening, etcetera). The food will be well cooked, tastier and nutritious than that cooked the conventional way. The time required to cook the food depend on the insolation, the amount of food placed into the oven, the type of food and the thickness of the portions - the thinner, the faster the cooking.



Mirror’s pair number	Cross-section’s geometry
1	Involute of a circle
2	CPC for a circular absorber
3	Straight line
4	CPC for a flat absorber

1. Container of hermetic closure
2. CPC for a cylindrical absorber
3. Flat mirrors
4. CPC for a flat absorber
5. Transparent cover
6. Stainless steel tray
7. Cap of the container

Fig. 5: Sketch of the *Tolokatsin* Solar Cooker model 1995. It has a 3D Multi Compound Concentrator built up with 8 single-curvature mirrors

Fig. 6: Photographs of two *Tolokatsin* solar cookers model 1995 with their containers opened showing their stainless steel trays with cooked meals inside them

The Constructal Law

Bejan's *Constructal Law* states that "for a finite-sized flow system to persist over time, it must evolve in such a way as to provide ever greater access to the currents that flow through it" (Bejan, 2016). After Bejan's statement, the constructal law has been applied to various engineering systems (Rocha et al., 2012) and more recently in systems of renewable energy by analyzing a solar chimney and an oscillating water column (Dos Santos et al., 2017). In these investigations the configurations that the involved elements should have in order to obtain the most adequate configuration to favor the flows involved were established.

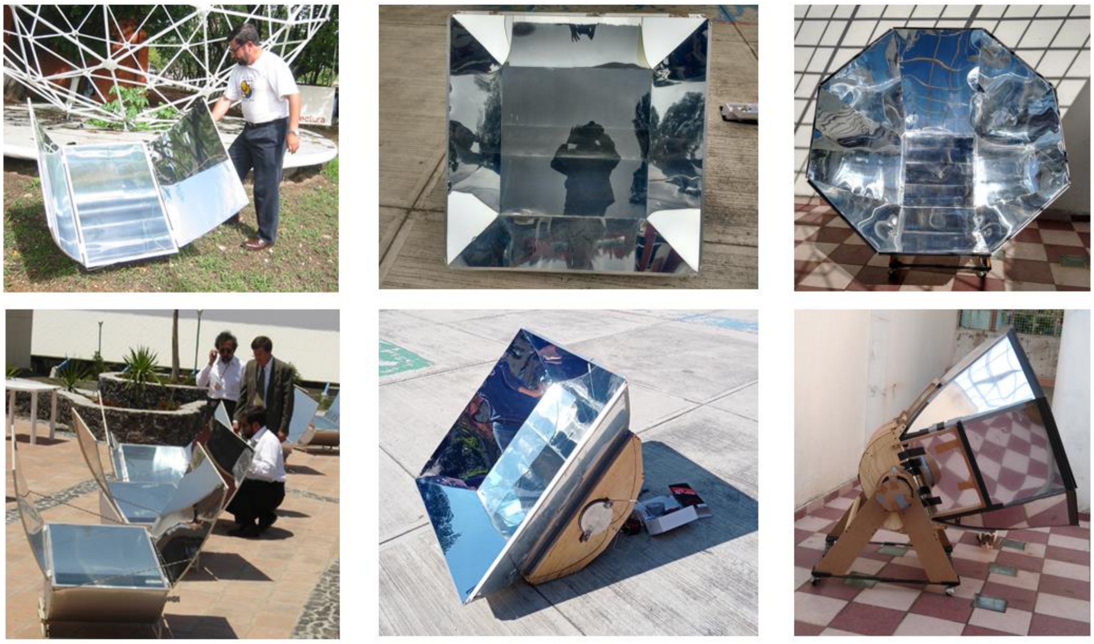
With regard to Multi Compound Solar Concentrators, which clearly belong to devices based on non-imaging optics, the flows are made of concentrated sunlight. Even though the first design of the Tolokatsin furnaces made more than 25 years ago seemed to be optimized in that a 3D solar concentration had been achieved from simple-curvature mirrors which allowed a great performance, according to the constructal theory the design would always be subject to improvement (there is no absolute optimum, cause the optimum evolves in time!). "Every where we look what we see is evolving because it is free to move and morph. Without freedom to change, there is nothing, no design, no evolution, and therefore no future" (Bejan, 2020). In the following lines an account of the evolution of these still-in-evolution-design solar furnaces (used not only as cookers, but sterilizers, ceramic ovens, etc.) is briefly described.

Evolution of the Tolokatsin Ovens

In figure 7 it is summarised the evolution of the Tolokatsin solar ovens. In Fig. 7a it is shown the original design made 25 years ago. That was a very succesfull one: it got an effective 3D concentration with acceptation angles of ~45°, wich allowed a stationary operation for about 3 hours with no need of adjusting its orientation to follow the Sun, enough time to cook black beans and all kind of foods. There was also no need to take care of the cooking process and the cook could do other tasks without having to expose himself to solar radiation.

The operation temperature beneth irradiances of the order of 700 W/m^2 were around 120°C, so practically all food recipes could be cooked on time. Lots of meals were prepared with this model in the campus of the Autonomous University of Mexico City, where every thursday there were free solar meals opened to every body to demostrate this simple technology. There still are some videos in the internet from those times.

However, in some cloudy days the elapsed time needed to cook was longer than three hours, and some difficult meals were not possible to cook on a reasonable time. To improve the ovens performance, the pair of parabolic mirrors -which also use to serve as hinged caps clearly visible in Fig. 7a- were substituted for two pairs of parabolic mirrors, as it is shown in the Tolokatsin V model (Fig. 7b), increasing in two the number of mirrors. This change improved the performance of the solar concentrator, but its complexity was increased too.

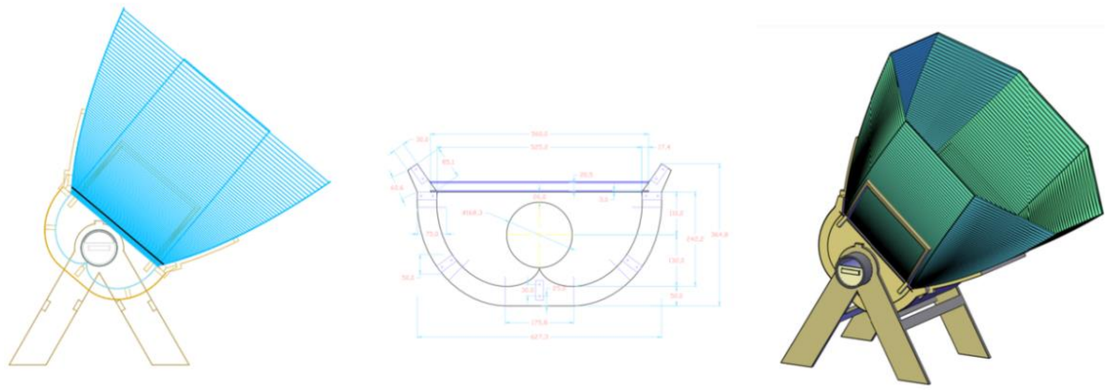


a b c

Fig. 7: Constructal evolution of the Tolokatsin solar cookers. a) 1995-model with 8 single-curvature truncated mirrors for a 3D solar concentration; b) Tolokatsin V, with 10 single-curvature truncated mirrors; c) Tolokatsin 2020 with 10 mirrors

Trying to get an even better performance, "to provide ever greater access to the light flow through the MCC" as Constructal Law dictates, the aim was now focused on: a) increasing the optical efficiency of the concentrator by reducing the average number of refletions of rays that imping on the absorber, b) to increase the concentration ratio (and so the stagnation temperature of the absorber), and c) to improve thermal insulation. This procedure led to the Tolokatsin 2020 model wich conceptual design is shown in figure 8. As in the previous design (Tolokatsin V), solar concentration is made in two stages: the first realised by an octogonal arrange of single-curvature parabolic mirrors optimaly truncated, and a second stage (with no contribution to the concentration ratio) consisting in a cavity limited by an involute mirror and two flat ones perpendicular to it, sealed by a double transparent cover, as it is shown in Fig. 8b.

The first stage has a regular octogonal acceptation area of lateral lenght L, and an exit square area, also with lateral lenght L. With this construction the geometric concentration ratio is $C_g = 2\sqrt{2} + 3$, with a semiangle of acceptation $\theta_0 = 15.782°$ which allows a stationary operation for more than two hours. Figure 9 shows the meshing of the MCC mirrors used for the ray tracing studies.



a) b) c)

Fig. 8: Conceptual design of the Tolokatsin 2020 solar oven. a) lateral view, b) cavity for the absorber, c) isometric view

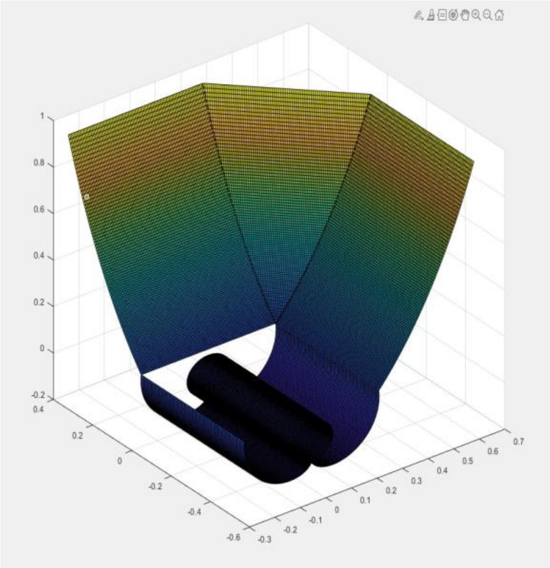


Fig. 9: Preparing the meshing of the MCC mirrors for the ray-tracing studies

6.1 A simple mathematic model

The basic procedure to optimise the design with the aim to get a very efficient operation can be sketched using the following extremmely simplified model.

Performing a rough energy balance on the absorber of the solar concentrator, it is obtained that the useful heat power $\dot{Q}_u$ is approximately:

$$\dot{Q}_u \approx A_c\, G_s\, \eta_o - A_r\left[\, \varepsilon\, \sigma\, T_r^{\,4} + \left(h\, \Delta T - \kappa\, \nabla T\right)\right] \qquad \text{(eq. 1)}$$

Here:

A_c is the acceptance area,

G_s is an effective solar irradiance at A_c , $G_s \approx (\cos\beta)G_b + \frac{G_d}{C_g}$ (from Rabl, 1976a), where G_b and G_d are the beam and diffuse irradiances, C_g is the geometric concentration and β is the incidence angle

η_o is the optical efficiency

A_r is the absorber exposed area

ε is the emittance of the exterior surface of the absorber

σ is the Stefan-Boltzmann constant

T_r is the effective mean temperature of the exterior surface of the absorber

h is the mean value of the heat transfer coefficient on the external surface of the absorber

κ is the mean value of the thermal conductivity of the insulation

In turn, the optical efficiency is modeled as:

$$\eta_o = f\, \alpha\, \tau\, \rho^{\,\langle N \rangle} \qquad \text{(eq. 2)}$$

Where:

f is an MCC *interception factor* (Duffie and Beckman, 2013) that takes into account mirror errors

α is the absorptance of the exterior surface of the absorber

τ is the transmittance of the transparent cover

ρ is the reflectance of the mirrors

N is the average number of reflections

The average number of reflections N is evaluated following the pionering work of Rabl, (1976b, 1977); factors f, τ are strongly dependent on the incidence angle of the rays on the acceptation area of the MMC. The optical analyzes were performed using the US NREL's software *SolTrace* (González-Mora & Rincón-Mejía, 2021).

These ray-tracing studies have some similarity to those performed by Cooper et al. (2013) on compound parabolic concentrators with polygonal apertures. Besides the energy balances, entropy calculations were made up in order to optimise the second-law efficiency inspired on early works on this thema (Petela, 1964 and 2005; Parrott, 1978).

Thus, the thermal efficiency of the MCC is finally given by:

$$\eta_t = \frac{\dot{Q}_u}{A_c\, G_g} \approx \frac{G_s}{G_g}\,\eta_o - \frac{1}{C_g G_g}\left[\,\varepsilon\,\sigma\,{T_r}^4 + (h\,\Delta T - \kappa\,\nabla T)\,\right] \qquad \text{(eq. 3)}$$

where $G_g = G_b + G_d$ is the global irradiance

Introducing the factors j and g, which compare the thermal losses for convection and conduction with that due to the radiation one (thermal radiation is the main and limiting heat loss in solar concentrators), and the ratio of diffuse to global irradiances:

$$j = \frac{(h\,\Delta T - \kappa\,\nabla T)}{\varepsilon\,\sigma\,{T_r}^4} \;\;;\;\; g = \frac{G_d}{G_b} \qquad \text{(eq. 4)}$$

$$=> \frac{G_s}{G_g} = \left(\frac{1}{1+g}\right)\left(\frac{(\cos\beta)C_g + g}{C_g}\right) \qquad \text{(eq. 5)}$$

With two limiting cases: a) $g \rightarrow 0$ (there is no diffuse irradiance), => $\frac{G_s}{G_g} \rightarrow \cos\beta$ (eq. 6)

and b) $g \rightarrow \infty$ (there is no beam irradiance), => $\frac{G_s}{G_g} \rightarrow \frac{1}{C_g}$ (eq. 7)

From eq. 3, the mean temperature of the absorber is approximately:

$$T_r \approx \left[\frac{\left(\frac{G_s}{G_g}\eta_o - \eta_t\right) C_g\, G_g}{(1+j)\,\varepsilon\,\sigma}\right]^{\frac{1}{4}} \qquad \text{(eq. 8)}$$

According to eq. 8, thermal efficiency is always lesser than the optical one, which is evidently the governing parameter to be optimised. When $\eta_t \rightarrow 0$, the absorber attains its stagnation temperture T_{stg} which maximum and minimum values, corresponding to the no diffuse irradiance and no beam irradiance, are respectively:

$$T_{stg\;max} \approx \left[\frac{(\cos\beta)\,\eta_o C_g G_g}{(1+j)\,\varepsilon\,\sigma}\right]^{\frac{1}{4}} = \left[\frac{(\cos\beta)\,\eta_o C_g G_b}{(1+j)\,\varepsilon\,\sigma}\right]^{\frac{1}{4}} \text{ and } T_{stg\;min} \approx \left[\frac{\eta_o\, G_d}{(1+j)\,\varepsilon\,\sigma}\right]^{\frac{1}{4}} = \left[\frac{\eta_o\, G_g}{(1+j)\,\varepsilon\,\sigma}\right]^{\frac{1}{4}} \quad \text{(eq. 9)}$$

Now, defining different functional groups that establish the degrees of freedom of the system that directly affect the thermal power of the MCC, an objective function can be determined. When performing the variation of the geometric parameters, the optimum operating values are determined (González-Mora et al, 2020).

6.2 Artisanal manufacture of the prototype

In spite of the relative complexity of this design, the manufacture of the first prototype of this model was made with easy in a backyard workshop with simple conventional tools, as it is shown in figure 10.

The materials utilised for the manufacture of this prototype were wood for the main structure of the legs and the cavity for the absorber, food grade stainless steel for the trays (this model can use two trays of 5 L each, or one alone of 10 L), a commercial aluminum tube (6 inches of nominal diameter) for the absorber with a self-formulated selective coating on this, two tempered flat glasses for the transparent cover of the cavity, celulosic thermal insulation, and 95% reflective anodized aluminum sheets for solar aplications for the ten mirrors of the MCC. The whole aparatus is monted on wheels for an easy manual orientation in two tracking axes.

Fig. 10: Artisanal construction of the first prototype of the Tolokatsin 2020 solar oven

Operational experience

More than 25 years of operation of different models of Tolokatsin solar ovens have proven their high performance, reliability and efficiency. Hundreds of international food recipes have been successfully prepared with them. However, for a more objective assessment of their performance, it is necessary to resort to already existing Technical Standards or to propose new methodologies for this purpose. The existence of very varied types of solar cookers used throughout the world has led to the establishment of standardized methodologies with which the different models can be compared. Amongst the most frequently reported regulations, the American Standard ASAE S580 (2003) and its revision (American Society of Agricultural and Biological Engineers, 2013), which provides a single figure of merit: the normalized heating power, stands out. However, it has the disadvantage of not evaluating the thermal efficiency nor the second-law efficiency of the cookers by seeking only to estimate the heating power normalised with respect to an irradiance of reference of 700 W/ m^2 when the cooker temperature is 50°C above the ambient temperature. Short before this standar, Funk (2000), has had proposed a procedure with two merit figures in his pionering proposal. Other authors have proposed especific procedures for their especific solar cookers (Mullik et al., 1996; Sharma et al., 2005; Zhao et al., 2018).

These procedures, although more well designed to be applied in box-type or panel-type solar cookers, generally involve a linear fit of temperature data against insolation times when a certain amount of water is heated, which is reasonable for kitchens that barely reach their boiling temperature, but fail when it comes to characterizing cookers that can widely exceed 100°C, since the losses due to thermal radiation are sensibly non-linear and a linearization of the performance curves is quite inadequate. This leads to proposing new methodologies for the characterization of concentrating solar cookers, among which the Tolokatzin cookers are included. The methodology that will be used in both Mexico and India as soon as the COVID pandemic subsides is that proposed by Khallafa et al. (2020), in which instead of using water, which has a low boiling temperature, it is proposed the use of glycerin as the test load material.

Meanwhile, the tentative application of the Standard ASAE S580 to the Tolokatsin V in a winter day (January 15, 2020) in Mexico City provided the data of Table1 that stand out a normalized heating power above 232 W when 7 kg of water (placed in two trays with 3.5 kg each) increased 50.5°C its temperature. The Tolokatsin 2020 model has more than double of that power, but we are cautiously waiting for newer results.

Tab. 1: Experimental results for the Tolokatsin V solar cooker

	Local hour	G_s (W/ m^2)	T_{amb} (°C)	$T_{H2O\ tray\ 1}$ (°C)	$T_{H2O\ tray\ 2}$ (°C)	T_{H2O}-T_{amb} (°C)	**Adjusted Power** (W)
1	10:20	518.6	19	20	30	1	197.62
2	10:40	584.3	20	30	23	6.5	233.86
3	11:00	631.6	21	40	28	13	214.72
4	11:20	696.8	21	51	36	22.5	245.19
5	11.40	699.7	23	61	45	30	244.12
6	12:00	752.8	23	71	56	40.5	272.01
7	12:20	736.0	24	80	69	**50.5**	**232.44**
8	12:40	733.3	24	88	82	61	233.21
9	13:00	733.6	25	95	93	69	117.21

Conclusions

It is a big mistake to continue burning fossil fuels or firewood for cooking in the world, when there is such a great solar resource, with which it is possible to cook any food almost any day of the year, using solar cookers of reasonable cost and high performance, self-built or industrialized. The massive use of solar cookers would significantly contribute to reducing greenhouse gas emissions and achieving all the SDGs of the 2030 UNO's Agenda. Solar cookers offer a great potential to fight energy poverty that deserves to be explored in the light of new technologies. They also offer new possibilities for caravans, cabins, hikers, recreation, and rest in areas of great ecological value.

To guarantee and excellent performance and a great reliability, even in unfavorable weather conditions for the use of other solar cookers, it is recommended those designed with the aid of nonimaging optics and the systematic application of the constructal theory, as the Tolokatsin solar ovens are. The main drawbacks of this type of solar cookers are their slightly greater manufacture costs and a rather sophisticated design; but even so, they can be fabricated with easy even in remote small villages of impoverished countries employing locally available inexpensive materials.

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References

American Society of Agricultural and Biological Engineers, 2013. Standard ASAE S580. Testing and reporting solar cooker performances, St. Joseph, MI, USA.

Bailis, R., Drigo, R., Ghilardi, A., Masera, O., 2015. The carbon footprint of traditional woodfuels. Nature Climate Change, 5, 266–272.

Balmes, J. R., 2019. Household air pollution from domestic combustion of solid fuels and health. J. Allergy Clin. Immunol., 143, 1988.

Bejan, A., 2016. Advanced Engineering Thermodynamics, 4th ed. John Wiley & Sons Inc., Hoboken.

Bejan, A., 2020. Freedom and evolution, Springer, Cham.

Boogaard, H., van Erp, A.M., Walker, K.D., Shaikh, R., 2017. Accountability Studies on Air Pollution and Health: the HEI Experience. *Curr Envir Health Rpt* 4, 514–522.

Conibear, L. et al., 2020. Environ. Res. Lett. **15** 094096.

Cooper T., Dähler F., Ambrosetti G., Pedretti A., Aldo Steinfeld, A., 2013. Performance of compound parabolic concentrators with polygonal apertures. Solar Energy, 97, 308-318.

Dos Santos, E., Isoldi L., Gomes M., and Rocha L., 2017. The constructal design applied to renewable energy systems, in: Rincón, E.A., de las Heras, A. (Eds.), Sustainable Energy Technologies. CRC Press, Boca Raton, pp. 45–59.

Duffie, J.A., Beckman, W.A., 2013. Solar Engineering of Thermal Processes, 4th ed. John Wiley & Sons Inc., Hoboken.

Funk, P.A., 2000. Evaluating the international standard procedure for testing solar cookers and reporting performance. Solar Energy 68 (1), 1–7.

González-Mora, E., Rincón-Mejía, E., Morillón, D., 2020. Diseño constructal de CPCs y la evolución de los diseños Tolokatsin. Proc. XVII Congreso Ibérico y XIII Congreso Iberoamericano de Energía Solar (in

Spanish). Lisboa. https://doi.org/10.34637/cies2020.1.2013

González-Mora, E., Rincón-Mejía, E., 2021. Optical evaluation of the Tolokatsin-2020 high-efficiency solar cooker. Proc. ISES SWC 2021, to be held 25-29 Oct. 2021.

Khallafa, A.M., Tawfikb, M.A., El-Sebaiic, A.A., Sagade, A.A., 2020. Mathematical modeling and experimental validation of the thermal performance of a novel design solar cooker. Solar Energy, 207, 40-50.

Kumar, P., Metha, S., 2016. Poverty, gender, and empowerment in sustained adoption of cleaner cooking systems: Making the case for refined measurement. Energy Research & Social Science, 19, 48-52.

Kundapur, A., 2018. A treatise on solar cookers, International Alternate Energy Trust, Udupi.

Lecuona, A., 2017. Cocinas solares. Fundamentos y aplicaciones, Marcombo (in Spanish), Madrid.

Mullick, S.C., Kandpal, T.C., Subodh, K., 1996. Testing of box-type solar cooker: second Figure of merit F2 and its variation with load and number of pots. Solar Energy 57 (5), 409-413.

Nandwani, S., 2004. Cocina-horno solar, Editorial Fundación UNA (in Spanish), Heredia, C.R.

Parrott, J.E., 1978. Theoretical upper limit to the conversion efficiency of solar energy. Solar Energy 21, 227–229.

Petela, R., 1964. Exergy of Heat Radiation. J. Heat Transfer 86, 187-192.

Petela, R., 2005. Exergy analysis of the solar cylindrical-parabolic cooker. Solar Energy 79, 221-233.

Rabl, A., 1976a. Comparison of solar concentrators. Solar Energy, 18, 93–111.

Rabl, A., 1976b. Optical and thermal properties of compound parabolic concentrators. Solar Energy, 18(6), 497–511.

Rabl, A., 1977. Radiation transfer through specular passages - a simple approximation. Int. Jour. Heat and Mass Transfer 20 (4), 323-330.

Rincón, E. et al., 1997. Desarrollo de cocinas solares con base en concentradores del tipo CPC. Proccedings XXI National Week of Solar Energy (in Spanish), ANES, Chihuahua.

Rincón, E.A., Durán, M.D., Lentz, A., 2009. New Solar Air Heater Based on NonImaging Optics for High-Temperature Applications, in: ASME 2009 3rd International Conference on Energy Sustainability, Volume 2. pp. 839–844.

Rocha, L.A.O., Lorente, S., and Bejan, A. (Eds.), 2012. Constructal Law and the Unifying Principle of Design. Springer, New York.

Rosenthal, J., Quinn, A., Grieshop, A.P., Pillarisetti, A., Glass, R., 2018. Clean cooking and the SDGs: Integrated analytical approaches to guide energy interventions for health and environment goals. Energy for Sustainable Development, 42, 152-159.

Sharma, S.D., Iwata, T., Kitano, H., Sagara, K., 2005. Thermal performance of a solar cooker based on an evacuated tube solar collector with a PCM storage unit. Sol. Energy 78, 416–426.

Smith, W.J., 1966. Modern Optical Engineering, McGraw-Hill, New York.

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

Winston, R., Jiang, L., Oliker, V., 2021. Nonimaging optics. Solar illumination system methods, design, and performance. CRC Press, Boca Raton.

World Health Organization, 2018. Household air pollution and health: key facts (https://www.who. int/news-room/fact-sheets/detail/ household-air-pollution-and-health, accessed 14 July 2021).

Zhao, Y., Zheng, H., Sun, B., Li, C., Wu, Y., 2018. Development and performance studies of a novel portable solar cooker using a curved Fresnel lens concentrator. Sol. Energy 174, 263–272.