Solar oven for intertropical zones: Optogeometrical design

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Abstract

In this paper, a novel design of a solar oven for the intertropical zones is presented. The oven box has seven faces instead of the six faces of most common designs reported in the literature, two of them are alternatively used as bases. This oven has four fixed mirrors to concentrate solar energy. The main advantage of this novel design is that the oven needs only four simple movements in order to obtain an adequate solar concentration throughout the year. This feature has been possible due to the optogeometrical design that is presented. A simple theoretical model of the oven concentration is developed. According to the model, the concentration achieved by the oven at noon is greater than 1.95 for all days of the year. In order to analyze the optical performance of the solar cooker, an experimental evaluation was conducted by using a scale model of the solar cooker and a heliodon.

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1. Introduction

Solar cookers, as their name indicates, are devices that use solar energy to raise the temperature of food to cook it. These solar devices are based on the simple principles of reflection, concentration, glazing, absorption and the greenhouse effect to store energy in order to increase the temperature. Various types of solar cookers exist, harnessing one or more of these principles. Solar cookers have attracted the attention of many researchers, in addition, many designers and small scale producers have, in recent years, made notable progress in the technical advancement of solar cookers. Since there is different availability of solar energy and there are different styles and traditions in the cuisine around the world, one can find a great variety of solar cooker designs.

Solar cookers fit into one of the following three categories [1]:

- Solar box cookers or solar ovens. They are insulated boxes with six or more faces, a glass cover at the top and usually include one or more adjustable reflective surfaces designed to increase the density of the solar energy collected. This category exploits both direct and diffuse solar radiation. In most cases, they require a minor intervention by the user in order to obtain a good exposure to solar energy.
- Concentrator cookers. They concentrate solar beam radiation on a cooking pot. In order to keep a good performance, a solar tracking system is required.
- Collector cookers (indirect solar cookers). They present two parts: a solar collector and a heat exchanger (a heat transfer fluid is used). These devices make use of diffuse and direct solar radiation. They are, however, rather complicated to build.

In 1997, Wareham [2] described some parameters for a solar cooker program. Wareham suggested in his paper that in order to replace fossil fuels with solar cookers, it

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requires: low cost materials, production facilities, funds for financing, government cooperation and a marketing program to develop field acceptance. Wareham indicated that a solar cooker must be of high quality, affordable, user friendly, light weight, rugged, stackable and family size.

The solar oven is the most common solar cooker reported in the literature and in comparative field tests, like the ones of the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) [1]. In two studies, conducted in 1991 and 1998 [3,4], a total of 168 different solar cookers were tested under real life conditions, of which 95 were ovens, 51 concentrator type and 22 collector type cookers [1]. Also, in the solar cookers test of the European Committee for Solar Cooking Research (ECSCR) [5], conducted in Almeria, Spain, in 1994, most of them were solar ovens.

There are many studies about the design, performance and acceptance of this type of solar cooker. Some are focused on the evaluation of the thermal performance [6–15]. Other studies have addressed the analysis of the materials used to build the solar cooker [16–18]. Also, proposals of mathematical models for describing the thermal behavior of solar ovens have been discussed and analyzed [19,20]. The social acceptance of these devices was also considered [21–23].

It is clear that solar ovens are a simple application of solar energy. However, in some countries, this technology has not presented social acceptance due to the following factors:

- In most of the cases, the process of cooking can take a long time (depending on the climatological conditions) and the use of a solar oven implies cooking under rays of the sun. This situation impacts using the solar oven.
- In order to reduce the time of cooking, some reflective surfaces are included to increase the solar density. In several solar ovens designs, the positions of the reflective surfaces and the orientation of the box to collect solar energy must be adjusted daily or monthly.

Because of the importance of social acceptance, the authors propose a solar oven classification, based on the frequency of movements or adjustments required for its operation reported in the literature, as follows:

- Solar ovens that need frequent movements or adjustments during the day, ranging from every 15 min (presented by [24,25]) to every 60 min (like the one presented by [27]). Most of the solar ovens proposed until now correspond to this type, and this is one of the main difficulties for social acceptance.
- Solar ovens that need movements or adjustments throughout the year, but do not require movements during the day. The authors found only one reported in the literature, the oven constructed by [28] that needs one reflector adjustment once a fortnight.
- Solar ovens that do not require any movement at all. All the solar ovens that correspond to this type are designed to be used in latitudes greater than the tropics (23°27′), where the rays of the sun do not change their north or south orientation very much throughout the year. Some examples are: the oven constructed in Pakistan (latitude of 32°N) by [29], the design of [30] developed for Lebanon (latitude 34°N) and the design of [31] for the north of India (latitude 28°N).

In this work, the design of a solar oven for the intertropical zone is presented. The novel aspect of this cooker is that the box has seven faces, two of them work as the base for specific seasons [32]. This design allows the oven, with only four movements during the year and three different positions, to catch enough solar energy to cook meals throughout the year. In the considered design the solar cooker will be able to cook 6 rations (considering the necessities of a typical family of 6 members), and the operation time is close to 4 h, from 10:00 a.m. to 2:00 p.m. It is important to indicate that the main Mexican meal takes place around 2:00 p.m. The organization of this paper is as follows: In Section 2, the criteria for the optogeometrical design and the resulting design are presented. A theoretical model of the optical performance was developed and is reported in Section 3. In Section 4, an experimental evaluation of the optical performance of the solar oven for a specific latitude and three representative days is described. In the Section 5, the main remarks for this research are presented.

2. Optogeometrical design

The objective of this research is to design a solar oven for the intertropical zones. The design is based on the idea of having two faces of the box that are alternatively used as the base of the solar oven and having four fixed reflectors. Thus, the solar oven is easy to use (with only a few movements throughout the year), and during the operation time, the solar oven obtains a good solar energy gain.

A two dimensional ray tracing technique was employed to design the geometry. The oven has been designed on the basis of the two days with the maximum solar declination: the day with maximum declination angle to the South (December 23) and the one to the North (June 22) and the winter and summer solstices. The main design condition is that, for these two selected days, the rays of the sun must fall perpendicular to the transparent face (cover) at noon at the design place in Mexico (latitude 18°50′N). This condition implies that the oven cover presents different inclinations. This was resolved by designing a box with two different bases (c and d in Fig. 1). As the cover has two possible inclinations, whose difference is 30°, the days when the oven has to be moved (Table 1) are defined by the condition that the angle formed by the cover and the sun rays at noon during all the year has to be less than or equal to 15°.

The inclination angles of the left and right reflectors, \(\phi_L\) and \(\phi_R\) in Fig. 1, which are North or South depending on

\(^{1}\) The designation of a reflector denotes its position relative to the cover.
the date, were determined as the respective mean value of
the angles that satisfy the condition that, at noon, all the
reflected rays from the reflector fall on the transparent
cover. The inclination angle $\phi$ of the East and West reflec-
tors (see Fig. 2) were determined considering the respective
mean value of the angles that satisfy the operation condi-
tion that all reflected rays from the reflector fall on the
transparent cover, from 10:00 a.m. to 2:00 p.m.

The geometry of the box was designed with seven faces:
two of them are the continuation of reflectors North–South
(b and e in Fig. 1), two are the alternating bases (c and d
in Fig. 1), two are the lateral faces (f and g in Fig. 2) and the
last one is the cover (a in Figs. 1 and 2). The height of the
box of the solar oven was designed considering enough
space to introduce two pots in order to cook 6 rations.
The North–South reflectors lengths ($l_L$ and $l_R$) were deter-
mined by the condition that, at noon, all the reflected sun
rays must fall on the bases (c and d). The width of the
box $w_a$ and the length $l$ of the East–West reflectors were
determined by the condition that, at 10:00 a.m., the specular
reflection of the solar radiation by the West reflector enters
the box. By symmetry, this condition is the same at 2:00
p.m. for the East reflector.

In the next section, in order to evaluate the performance
of the oven throughout the year, a theoretical model was
developed.

### 3. Theoretical model of the performance

To calculate the solar energy collected by the solar oven,
a theoretical model based on the one proposed by Peres
and Karlsson [34] was developed. This model allows us
to calculate the total solar energy per unit area and unit
time that is collected by the solar oven through the mea-
sured global solar radiation in the horizontal plane per unit
area and unit time.

The model proposed by Peres and Karlsson [34] is appli-
cable to long solar collector arrays (flat and CPC) with
only one reflector; in those arrays, the perpendicular plane
to the collector and to the reflector is a vertical plane. The
developed model for the oven considers the individual con-
tribution of each reflector in an independent form, except
for the shadow. The present model includes the case where
the perpendicular plane to the cover and the reflector is not
vertical, as is the case for East–West reflectors.

The model proposed in this section considers only the
contribution of the direct solar radiation. The incident
radiation onto the solar oven, $q_0$, is composed of the direct
incidence onto the cover, $q_c$, and the contribution from
each reflector.

$$q_0 = q_c + q_N + q_S + q_E + q_W,$$

where $q_N$, $q_S$, $q_E$ and $q_W$ are the contribution due to the
North, South, East and West reflectors, respectively.

The performance factor, $C$, that measures the gain due
to the cover inclination and the presence of the reflectors,
is defined as

$$C = \frac{q_0}{q_b},$$

where $q_b$ is the radiation onto the cover as if it were in a
horizontal plane. Similarly, the performance factor due to
each one of the terms in Eq. (1) is defined as

$$C_i = \frac{l_i}{q_b},$$

where $i = C, N, S, E$ and $W$.

It is important to note that $C$ and $C_i$ depend on the
time.
3.1. Cover contribution

The radiation per unit of time falling directly onto the cover is calculated through

\[ q_c = I_z A_z \cos h \cos h z ; \]  

where \( I_z \) is the solar radiation in the horizontal plane per unit time and per unit incident area, \( A_z \) is the cover area, \( h_c \) is the angle between a direct ray from the sun and the cover normal and \( h_z \) is the zenith angle. ²

3.2. North and South reflectors contribution

The North and South reflectors satisfy the conditions of Peres and Karlsson’s model [34]. A summary of the equations involved is presented, for the North and South reflector, the general subscripts \( r \) must be replaced by the subscripts N (North) and S (South), respectively.

To determine the contribution of a reflector to the solar energy that enters into the oven per unit of time (\( q_r \)), it is first necessary to determine the apparent solar altitude, \( a_p \), that is the projection of the solar altitude onto the plane perpendicular to the cover and the reflector measured from the side of the reflector, \( 0^\circ < a_p < 180^\circ \). The angle \( a_p \) is given by the following expression

\[ a_p = \arctan \left( \frac{\tan z_s}{\cos (\gamma_s - \gamma_c)} \right) , \]  

where \( \gamma_s \) is the solar azimuth angle of the plane, \( \gamma_c \) is the azimuth angle of the plane perpendicular to the cover and the reflector measured from the side of the reflector, \( 0^\circ < \gamma_s < 180^\circ \); the South is defined as \( \gamma_c = 0 \), the East is negative and the West is positive), and \( z_s \) is the solar altitude (see Fig. 3).

The projection of the normal radiation onto the plane perpendicular to the cover and reflector, \( q_p \), is given by

\[ q_p = \frac{I_z A_r \sin \beta_r}{\sin (z_s + a_p)} , \]  

where \( A_r \) is the reflector area.

To evaluate the contribution of each reflector, it is necessary to discriminate between four different cases distinguished by the value of the apparent solar altitude with respect to two critical angles

\[ a_{p1} = 2 \beta_r + \arctan \left\{ \frac{\sin \beta_c - \frac{a_p}{2} \sin \beta_r}{\cos \beta_r + \cos \beta_c} \right\} ; \]  

and

\[ a_{p2} = \beta_c , \]  

where \( \beta_r \) and \( \beta_c \) are the reflector and cover tilt angles from the horizontal plane, measured perpendicularly from the union between them, \( L_r \) and \( H \) are the reflector and cover lengths, respectively, also measured perpendicularly from their union.

For \( a_p < \beta_r \), the reflector makes a shadow on the cover, which means the contribution of the reflector is negative and is given by

\[ q_r = -q_c \frac{L_r \sin (\beta_r - a_p)}{H \sin (\beta_c + a_p)} . \]  

The second case occurs when \( \beta_r \leq a_p < a_{p1} \). In this case all the reflected radiation by the reflector falls onto the cover, giving a contribution of

Fig. 3. Angles involved to determine the contribution of each reflector.

² Definitions of the solar variables are taken from [33].
\[ q_t = q_p \frac{L_r}{H} \rho \sin(\beta_t - \beta_r), \quad (10) \]

where \( \rho \) is the reflectance of the reflector.

The third case happens when \( \alpha_p \leq \alpha_p < \alpha_{p2} \). The apparent solar altitude is so high that some of the reflected radiation is lost over the cover, then

\[ q_t = q_p \rho \sin(2\beta_t + \beta_c - \alpha_p). \quad (11) \]

The fourth case is present when \( \alpha_p \geq \alpha_{p2} \). For this condition, all the reflected radiation by the reflector is lost over the cover, thus,

\[ q_t = 0. \quad (12) \]

### 3.3. East and West reflectors contributions

For East and West reflectors, the plane perpendicular to the cover and to the reflector is not a vertical plane. It presents an angle with respect to the vertical given by the inclination of the cover in the North-South direction. This angle is denoted by \( \beta^* \). The modification made to Peres and Karlsson’s model to account for this fact is presented here.

The apparent solar altitude, \( \alpha_p \), on the vertical plane with the same orientation of the cover-reflector axis is given by

\[ \alpha_p = \arctan \left( \frac{\cos \beta^* \tan \gamma_i \cos(\gamma_i - \gamma_c)}{\cos \gamma_i \sin \gamma_p \cos \beta^*} \right). \quad (13) \]

In these reflectors, the projection of the radiation onto the plane perpendicular to the cover and to the reflector, \( q_p \), is given by

\[ q_p = \frac{I_z \sin \gamma_i \cos \beta^*}{\cos \theta_i \sin \gamma_p \cos \beta^*}. \quad (14) \]

To evaluate the contributions of the East and West reflectors, there are the same four cases as in the Peres and Karlsson model, and Eqs. (7) to (12) are applicable, only Eq. (9) is modified to account for the shadow onto the North or South reflector, becoming

\[ q_t = -q_i \frac{L_r}{H} \frac{\sin(\beta_t - \alpha_p)}{\sin(\beta_c + \alpha_p)} - q_i \left( \frac{L_r}{H} \frac{\sin(\beta_t - \alpha_p)}{\sin(\beta_c + \alpha_p)} \right), \quad (15) \]

where \( q_i \) is the contribution due to the North or South reflector, \( i = N \) if \(-90^\circ < \gamma_i < 90^\circ\); otherwise, \( i = S \).

It is important to indicate that the model proposed does not consider the reflection losses of unpolarized radiation while passing from the environment to the transparent cover of the oven. Since the acceptance angle is less than \( 15^\circ \), these reflection losses are up to 4%.

About the influence of shading of the East and West reflectors during morning and afternoon, respectively, we need to emphasize that the solar cooker was designed to operate around lunch time in Mexico. Lunch time in Mexico is the principal meal of the day, and it is taken around 2:00 p.m. local time. Another important point is that the standard time of most of the country has been shifted ahead one hour in winter and two hours in summer. For this reason, morning sunlight before 9:00 (solar time) has not been considered in designing the solar oven. Moreover, a simple calculation based on the air mass [35] and the
The angle of sunlight incident at 9:00 solar time gives a radiation of 0.58 times the radiation intensity of noon sunlight and for 8:00 solar time it is 0.37. Therefore, these simple calculations justify the fact that the solar cooker is not designed considering the early hours of the morning. In the case of the afternoon, as it was mentioned before, the principal meal in Mexico is around midday, thus cooking activities are not important after lunch time.

As an example, the theoretical performance factor of each reflector for March 8 is depicted in Fig. 4. This date corresponds to a minimum value for the performance fac-

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3 These calculations were performed considering AM = 1.5, where the effective transmission of sunlight through the glass cover at an angle of 60° (9:00 a.m.) is \( \tau = 0.95 \) and AM = 2 where the effective transmission at an angle of 45° (8:00 a.m.) is \( \tau = 0.93 \).
tor as shown in Fig. 5. It is important to indicate that for all the days of the year, the maximum value of solar energy collected by all the reflectors is presented at noon.

3.4. Annual performance factor of the solar cooker

To evaluate the oven performance throughout the year, the performance factor $C$ at noon was calculated using the theoretical model. The results are presented in Fig. 5. As it is expected from the design conditions, the maximum is achieved for December 23, attaining a value of 2.61. Also, June 22 is a local maximum with a concentration of 2.03. The annual average for the performance factor obtained at noon by the oven is close to 2.20. The labels d–s, c–s and c–n, represent the face used as base and the orientation of the oven, as defined in Table 1 and the vertical lines indicate the days of oven movements.

4. Experimental evaluation of the optical performance

In order to analyze the optical performance of the solar oven, an experimental evaluation was conducted for the latitude 18°50′N for three representative days: March 8, July 29 and December 23, for each hour from 10:00 to 12:00 h. The experimental tests were done by using a scale model of the solar oven (scale 1:6) and a heliodon. A heliodon is an efficient tool for studying the patterns of the shadows and how the beam radiation is reflected into the solar oven. The heliodon used in this research (Fig. 6) consists of a rotatory platform, where the scale model is set and a lamp that simulates the sun. The position of the lamp can be adjusted to represent the beam radiation of a given latitude (<70°), for a specific day and hour.

A preliminary evaluation of the solar oven was performed to obtain the contribution area of each reflector. The technique consists of taking photographs of the model and estimating the illuminated area of the cover by each reflector. This was done by putting a non-reflective cover on the reflectors that are not being analyzed for the three typical days from 10:00 to 12:00 h. Fig. 7 shows an example of these photographs. The results show that all the reflectors have a significant contribution, their relative importance depending on the day and hour.

The evaluation of the radiative energy collected by the solar oven was done using an array of calibrated photore sistances distributed equidistantly on the cover area of the oven scale model.

The experimental total performance factor and the theoretical predictions for March 8, July 29 and December 23 are depicted in Fig. 8. Although the experimental and theoretical results have deviations up to 20%, the theoretical model is a useful simple tool. The results encourage the construction of the solar oven.

5. Conclusions

The performance factor model, although simple, is a useful tool to evaluate the gain of solar energy due to the inclination of the cover and the presence of the reflectors throughout the year, and it can be used to evaluate the energy that the solar oven receives if the insolation data over the horizontal plane is available.

The theoretical model results show that, at noon, the solar cooker achieves a concentration level greater than 1.95 throughout the year. It is expected that these concentration values are enough to increment the meal temperature for the cooking process.
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