

Design, realisation and experimentation of a solar cooker fitted with an ellipsoidal concentrator: Preliminary results of cooking tests

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Abstract. This article is about the realization and experimentation of an elliptical solar cooker. This prototype has a single focus and a reflective surface made of galvanized sheet. Its opening diameter is 120 cm and focal length is 60 cm. In a first step, Cooking Tests of six eggs in 0.5 L of water were carried out by fixing the maximum cooking time to 2 hours. The first results showed that the cooking of the eggs was partial. Despite adequate illumination, the temperature 82°C, at which starts the cooking of certain foods according to “International Solar Cooker”, could not be reached. Thus, a glass cubic box was built that served as an envelope for the pan. In 60 minutes with this new configuration, a temperature of 88.23°C was reached, which is widely more than the 82°C required. After 80 minutes of cooking, a temperature of 92.12°C was reached. Finally, after 80 minutes of cooking, all six eggs were completely cooked. In the second step, the reflective surface was coated with mirror. In such configuration, seven eggs were perfectly cooked after 40 minutes of cooking in 0.5 litres of water. 250 grams of rice were also cooked after 80 minutes of cooking, in 0.50 litres of water. Experiments were made simultaneously with a parabolic concentrator solar cooker. Efficiency calculations showed that the ellipsoidal concentrator solar cooker and the parabolic concentrator solar cooker have almost the same efficiency, with a slight advantage for the ellipsoidal concentrator solar cooker.

1. Introduction

Energy needs for cooking are enormous. In most developing countries, the energy supply for cooking relies so far on conventional sources of energy, such as firewood collected from forest and charcoal. Those energy sources linked to biomass lead to depletion of the forest and therefore to the degradation of the environment.

The use of solar energy is one of the alternative solutions which is clean, renewable and sustainable. In Côte d’Ivoire, solar irradiation is important. The daily total radiation varies of course from 3 to 5 Kwh/m², depending on the regions [1]. Solar cookers are therefore promising. The use of solar energy for cooking requires high temperatures. Such temperatures are obtained by means of concentration systems. Some studies have been made about the parabolic concentrator solar cookers. [2-5]. The hot box solar cookers have also been studied [6,7]. Another type is the conical solar cooker, which has been studied by several researchers [8,9]. In Côte d’Ivoire, the technology of solar cookers is not well known and our team is so far the only one which is involved in the design and building of solar cookers. Our studies include also hot box, parabolic, spherical, conical ...types of solar cookers.



2. Design and description of the ellipsoidal concentrator

2.1. Design of the concentrator

2.1.1. Co-ordinates x and calculation for the designed ellipsoidal concentrator. An ellipse is defined as “the set of all points P such that the sum of the distances between P and to distinct fixed points, called the foci, is constant”. The ellipse is represented in figure 1, with its two focal points F1 and F2 along the Y axis.

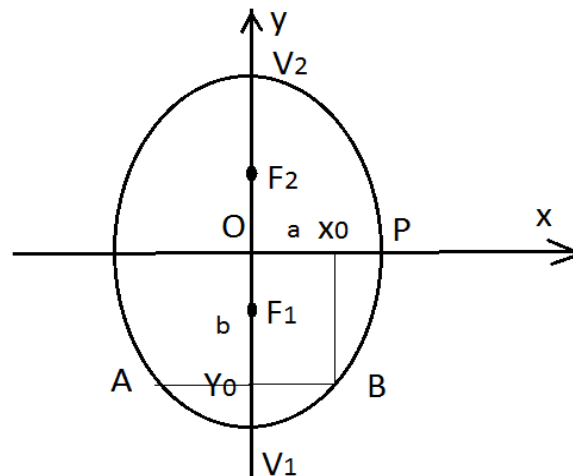


Figure 1. Representation of an ellipse showing its two focal points.

For the design of the concentrator, only the focal point F1 was considered. In the x and y co-ordinates system, the ellipse equation is expressed as

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \quad (1)$$

a and b are respectively the semi-minor axis and the semi-major axis of the ellipse. On figure 1, a and b are given by $a = OP$; $b = OV1$. The two points $V1$ and $V2$ are the vertexes. The ellipse is characterized by the distance $c = OF1 = OF2$; this distance is expressed as

$$c = \sqrt{b^2 - a^2} \quad (2)$$

As for the focal length f , it is given by

$$f = V1 F1 = V1 O - F1 O \quad (3)$$

Hence, f is expressed as

$$f = b - c = b - \sqrt{b^2 - a^2} \quad (4)$$

For the design of the concentrator, a truncated ellipsoid is considered. As shown on figure 1, AB is the opening of the concentrator. Let $X0$ and $Y0$ be the coordinates of B . Hence, the opening diameter is $d = 2X0$. In the design process, we selected a so that $a = d$. Hence, for a given value of d , X was expressed as

$$x_0 = \frac{a}{2} = \frac{d}{2} \quad (5)$$

As the semi-minor axis, a was chosen so that $a = d$, for a chosen value of d , a is gotten. From equations (1) and (5), one gets

$$y_0 = 0.866b \quad (6)$$

As for the depth h of the ellipse, it is expressed as

$$h = b - y_0 \quad (7)$$

Combining equations (6) and (7), one gets

$$h = 0.13397b \quad (8)$$

From equations (2) and (5), one gets

$$c = \sqrt{b^2 - d^2} \quad (9)$$

Hence, the focal length is expressed as

$$f = b - \sqrt{b^2 - d^2} \quad (10)$$

2.1.2. Calculation of the length of the arc of the ellipse. An arc of ellipse is represented on figure 2.

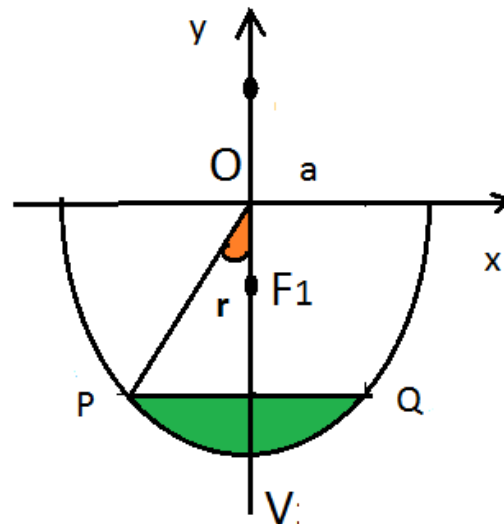


Figure 2. Representation of an arc PQ of the ellipse.

Let P be a point of the ellipse and r be the angle between the semi-major axis OV and the line OP. The coordinates of P are expressed as

$$\begin{aligned} x &= a \sin r \\ y &= b \cos r \end{aligned} \quad (11)$$

The length of the arc PV is expressed as [10]

$$s = \int_{r_v}^{r_p} \sqrt{x'^2 + y'^2} dr \quad (12)$$

The eccentricity e of the ellipse is expressed as

$$e = \frac{\sqrt{b^2 - d^2}}{b} \quad (13)$$

Let L be the whole ellipse length. It is expressed as [10]

$$L = 2\pi b \times [1 - \left(\frac{1}{2}\right)^2 \times \frac{e^2}{1} - \left(\frac{1}{2} \times \frac{3}{4}\right)^2 \times \frac{e^4}{3} - \left(\frac{1}{2} \times \frac{3}{4} \times \frac{5}{6}\right)^2 \times \frac{e^6}{5} - \left(\frac{1}{2} \times \frac{3}{4} \times \frac{5}{6} \times \frac{7}{8}\right)^2 \times \frac{e^8}{7} - \dots] \quad (14)$$

There are some approximations for the calculation of L . One of them is the Fagnano approximation which is expressed as [10]

$$L = \pi \times \left[\frac{3}{2}(a + b) - \sqrt{a \times b} \right] \quad (15)$$

Another approximation is the following [11]

$$\pi \times (a + b) \leq L \leq \pi \times \sqrt{2 \times (a^2 + b^2)} \quad (16)$$

Let the arc- PQ be considered shown on figure 2. Its length s is calculated from the knowledge of the angle θ between the semi-major axis OV and OP, when PQ is the opening diameter of the concentrator-. The value of s is expressed as

$$s = \frac{2\theta}{2\pi} L \quad (17)$$

where θ is expressed in radian. This angle θ is calculated from the' following relationship.

$$x_0 = a \times \sin\theta \quad (18)$$

2.2. Description of the ellipsoidal concentrator experimented

The opening diameter d of the concentrator was chosen to be $d = 1.2$ m. Therefore, by using equation (5), one gets $a = 1.2$ m. As for the depth h of the ellipse, it was chosen to be $h = 0.20$ m. Then from equation (8), one gets $b = 1.4928$ m. Finally, from equation (10), one gets the focal length f . It is found $f = 0.60$ m. The concentrator was built using steel rods. It has six facets. Its reflective surface. is made of galvanized steel sheet (which is easily found in our country) divided into six facets The base of the black painted pan is held by a collar at a distance l from the focal point, called the back axial distance. This distance l is gotten from the following relationship

$$d_2 = \frac{l \cdot d}{f - h} \quad (19)$$



Figure 3. Photography of the elliptic arc cut in plywood.

where d_2 is the diameter of the pan, f the focal length, h the depth of the ellipsoid and d the opening diameter. The eccentricity calculated from equation (13) is $e = 0.594835$. The whole length L of the ellipse calculate from equation (14) is $L = 8.48$ m. As the calculation of L is limited in equation (14), to e^8 , $L = 8.4$ was considered. From equation (18), one gets $\theta = 30^\circ$. Then the theoretical value of the length of the arc of the ellipse, calculated from equation (17), is $s = 1.36$ m. An experimental building of the ellipse's arc was made by plotting the x ; y coordinates on a plywood sheet using equation (1).

From this plotting, the length s was measured and found to be $s = 1.32$ m, which is close to the theoretical value. Photography of the elliptic arc cut in plywood is shown on figure 3. By using this elliptic plywood, elliptical arcs were made with steel rods. The steel rods were assembled to make the six facets of the concentrator. Then the galvanized steel sheets were soldered on the elliptical arc to make the reflective surface. Finally, for the second set of experiments, square pieces of mirror whose dimensions are 0.05×0.05 m² were set on the galvanized steel.

The opening of the concentrator is circular.

Photography of the experimental device with the ellipsoidal concentrator is shown on figure 4 (showing the back of the concentrator) and figure 5 (showing the front of the concentrator).

The glass cube is shown on figure 6 where it is placed on a chair. It is also seen on figure 7 where it envelops the absorber which is the cooking pan.



Figure 4. Photography showing the back of the ellipsoidal concentrator.



Figure 5. Photography showing the front of the ellipsoidal concentrator.



Figure 6. Photography showing the glass cubic box.

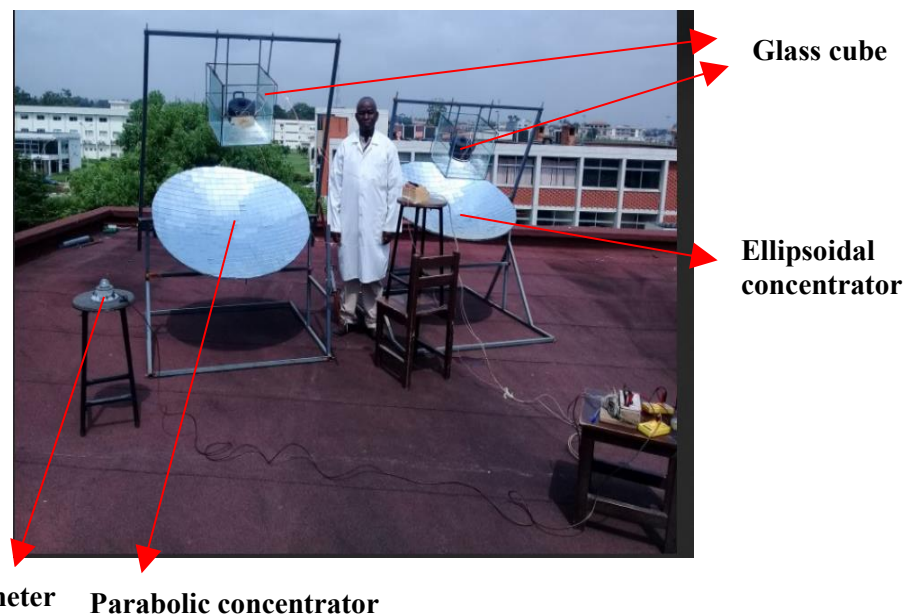


Figure 7. Experimental device with the ellipsoidal and the parabolic concentrators.

3. Experimental study of the ellipsoidal concentrator solar cooker

Several cooking tests of eggs and rice were carried out. For the first experiment, the tests were made with 0.5 litres of water and six eggs in the pan. During the tests, temperature measurements were performed by using platinum resistance thermometers. Temperature data were recorded at a time interval of 10 minutes. The measured temperatures were the ambient temperature T_a , the temperature T_{bas} at the bottom of the pan and the cooking temperature $T_{cuisson}$. An Eppley –type pyranometer was used to record global solar radiation, at time interval of 10 minutes. Every 20 minutes, the ellipsoidal concentrator was oriented in front of the sun by means of a manual tracking system. Two configurations were studied. In the first configuration, cooking tests performed on March 22th 2017 without any glass cubic box around the pan. The maximum cooking duration was 2 hours, from 11:00

to 13:00; the maximum cooking temperature reached was 74.39°C, which is lower than 82°C. According to “Solar Cooker International” [12], foods start to cook between 82° and 91°C. Figure 8 shows the evolution of temperatures and solar radiation E with time, for the experiment without glass cubic box. The cooking of the six eggs was not perfect. This experiment showed that thermal losses of the pan, by radiation and convection, were very important. Consequently, in the second configuration, a glass cubic box has been installed, that served as a wrapper for the pan. The aim was to reduce the thermal losses. Figure 5 shows the evolution of temperatures with time in that second configuration. After 60 minutes on March 23th, the cooking temperature was 82.23°C. After 80 minutes of cooking, the cooking temperature reached 92.12°C and the six eggs were completely cooked. Figure 9 shows the evolution of temperatures and solar radiation E with time, for the experiment with the glass cubic box

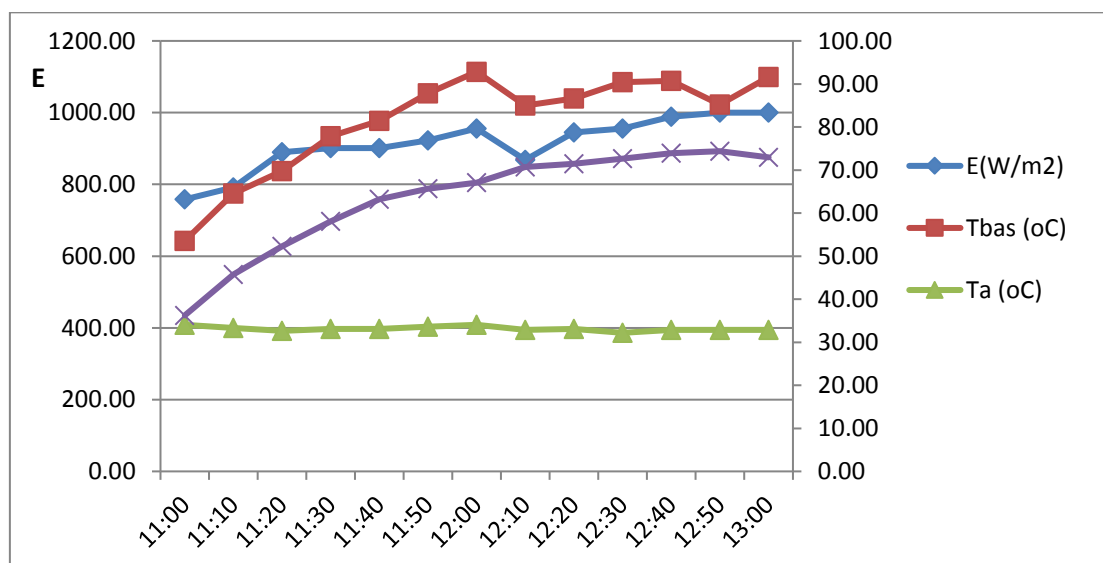


Figure 8. Temperatures and solar radiation evolutions for cooking without glass cubic box.

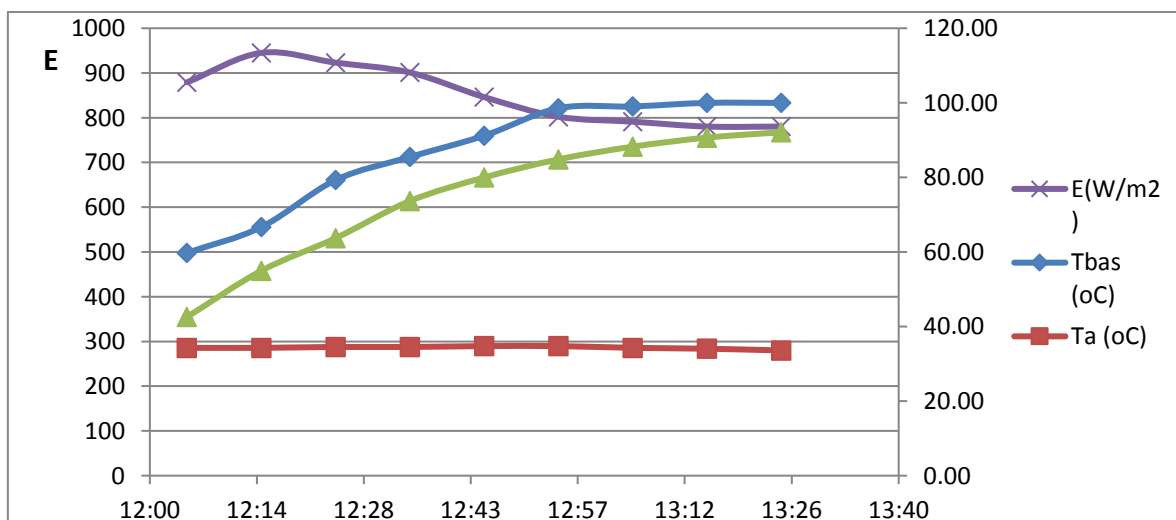


Figure 9. Temperatures and solar radiation evolutions for cooking with glass cubic box.

Farther experiments were made to improve this result. For that the reflective surface was coated with mirror, in order to increase its reflection coefficient. The mirror was cut in square pieces whose

dimensions are $0.05 \times 0.05 \text{ m}^2$. In that configuration, during a cooking test made on October 25th 2017, 07 eggs were perfectly cooked in 0.5 litres of water after 40 minutes of cooking. The cooking test was made simultaneously on the elliptic cooker and on a parabolic cooker; the two cookers have the same opening diameter. Figure 10 shows the evolutions of temperatures and solar radiation during the cooking of the seven eggs. The cooking temperature reached was 94.64°C and 100°C respectively for the elliptic and the parabolic cooker, while the maximum T_{bas} (the pan's bottom temperature) reached was 116.79°C .

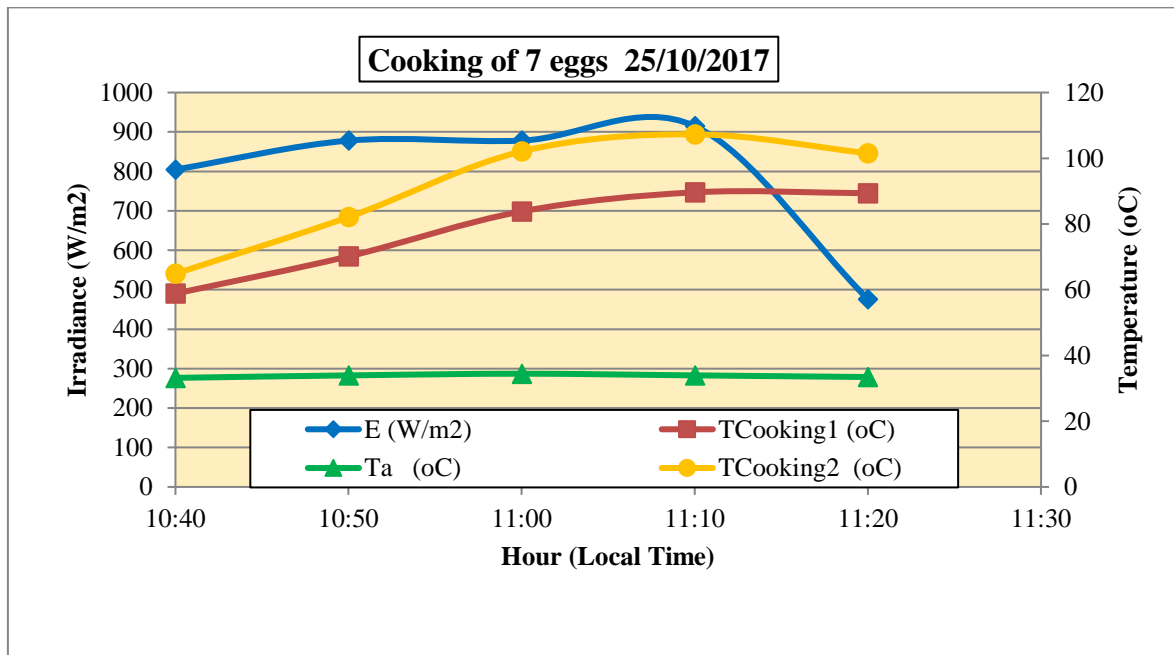


Figure 10. Temperatures and solar radiation evolutions for cooking of 7 eggs with glass cubic box and concentrators coated with mirror for the elliptical (TCooking1) and the parabolic (TCooking2) cookers.

Moreover, after coating the reflective surface with mirror, cooking tests of rice were carried out. 250 grams of rice in 0.5 litres of water were cooked after 80 minutes of cooking. The maximum cooking temperature reached for the rice was 104.10°C and 114.11°C respectively for the elliptic and the parabolic cooker, while the maximum T_{bas} (the pan's bottom temperature) reached was 168.86°C . A better setting of the back axial distance should improve the cooking temperature, because of the high temperature obtained for the pan's bottom. Figure 11 shows the evolutions of temperatures and solar radiation during the cooking of rice.

The evolution of T_{bas} (the pan's bottom temperature) for the two cookers is shown on figure 12.

The maximum T_{bas} temperatures reached were 168.86°C for the elliptical cooker and 174.98°C for the parabolic cooker. The results with the elliptical concentrator will be improved by making a better setting of the back axial distance and by increasing the number of facets of the concentrator. A new ellipsoidal concentrator is being built in that way.

Other cooking tests were made. On October 21th 2017, 05 eggs were perfectly cooked in 0.5 litres of water after 40 minutes of cooking. The maximum cooking temperature reached was 100°C for both cookers. The same experiment was made on October 22th 2017 and all the 05 eggs were perfectly cooked

On October 26th 2017, 10 eggs were perfectly cooked in 0.5 litres of water after 40 minutes of cooking. The maximum cooking temperature reached for t was 91.48°C and 100°C respectively for the elliptic and the parabolic cooker

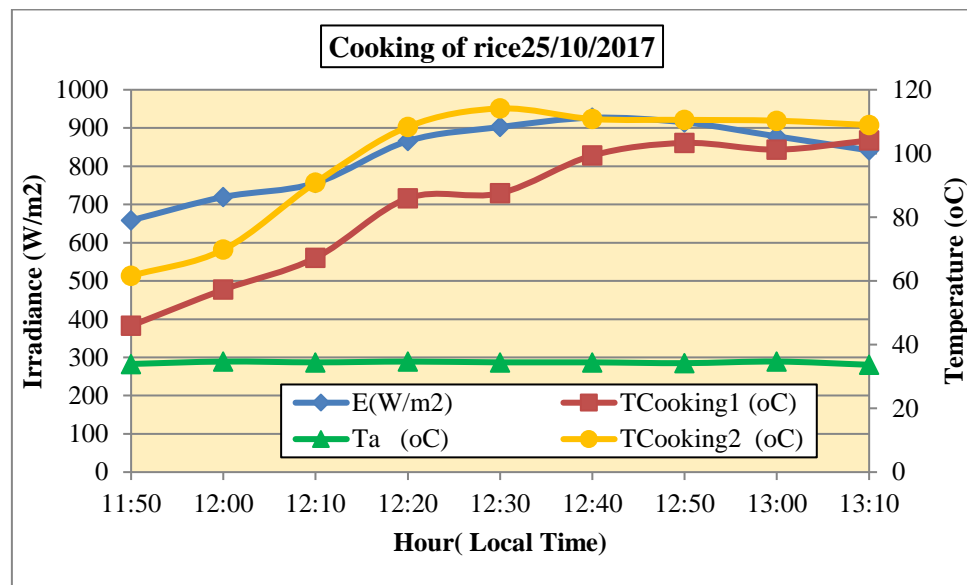


Figure 11. Temperatures and solar radiation evolutions for cooking of rice with glass cubic box and concentrators coated with mirror for the elliptical (TCooking1) and the parabolic (TCooking2) cookers.

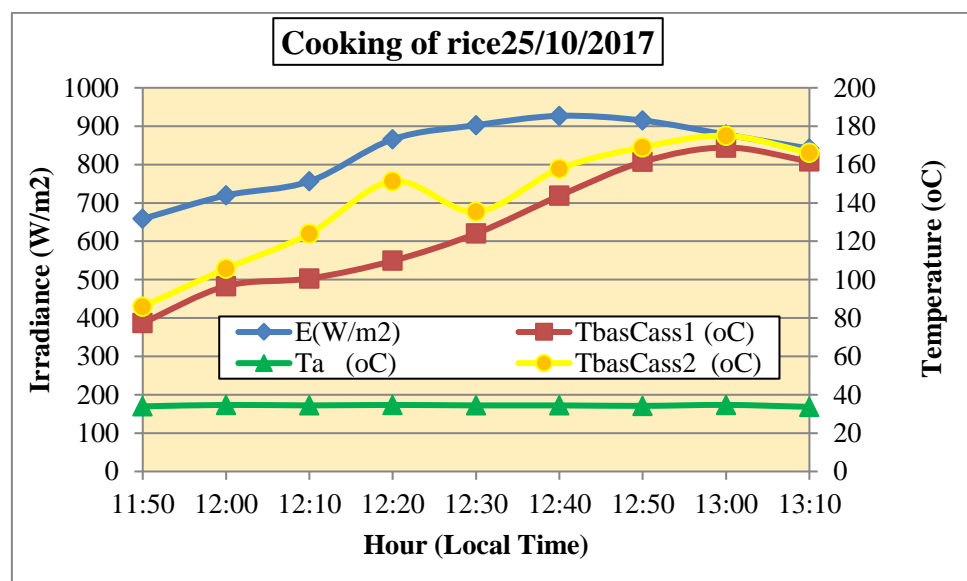


Figure 12. Pan's bottom temperatures and solar radiation evolutions for cooking of rice with glass cubic box and concentrators coated with mirror for the elliptical (TbasCass1) and the parabolic (TbasCass2) cookers.

On October 26th 2017, 250 grams of rice were perfectly cooked in 0.625 litres of water after 80 minutes of cooking. The maximum cooking temperature reached was above 100°C for both cookers

Hence, in the configuration for which the reflective surface was coated with mirror, six cooking tests were performed. In all the cases, the eggs and rice were perfectly cooked.

4. Efficiency of the ellipsoidal concentrator solar cooker

To evaluate the efficiency, we need to make an energy balance of the receiver.

4.1. Energy balance of the receiver with the glass cubic box

If Q_u is the useful power received by the receiver, the energy balance is given by the difference between the absorbed power Q_{abs} and the losses P .

Q_{abs} is expressed by [13]:

$$Q_{abs} = \eta_0 I_p C_g \rho \gamma A_{abs} \quad (20)$$

Where $\eta_0 = (\alpha\tau)$ is the optical efficiency, α = Receiver absorption coefficient, τ = Transmission coefficient of the glazing (if any), I_p = Direct irradiance of the radiation (W/m^2), ρ = Reflection coefficient of the parabolic reflector, γ = Intercept coefficient expressed as [13]:

$$\gamma = 1 - \exp \left[-820 \left(0.7 \cdot \frac{r}{f} \right)^2 (1 + \cos(\phi)) \right] \quad (21)$$

where ϕ is the opening angle of the parabola in degrees.

r designating the exergy is governed by equation (22) [7]:

$$r = 1367 * \pi * \left(\frac{d}{2} \right)^2 * \left(1 - \frac{T_i}{T_f} \right) \quad (22)$$

where T_i = Initial temperature of the pan ($^{\circ}C$), T_f = Final temperature of the pan ($^{\circ}C$).

A_{abs} = Total surface receptor that is expressed by:

$$A_{abs} = \pi \cdot \frac{d_2^2}{4} + \pi \cdot d_2 \cdot h_{abs} \quad (23)$$

where d_2 = Receiver opening diameter, h_{abs} = Receiver height, equation (20) can be rewritten as follows:

$$Q_{abs} = A_{abs} \cdot P_{abs} \quad (24)$$

with

$$P_{abs} = \eta_0 \cdot I_p \cdot C_g \cdot \rho \cdot \gamma \quad (25)$$

$$C_g = A_{op} / A_{abs} \quad (26)$$

where C_g is the geometric concentration coefficient of the concentrator, with A_{op} = Aperture area of the collector.

Losses P are expressed by:

$$P = A_{abs} \cdot h_{rc} \cdot (T_{abs} - T_a) \quad (27)$$

where

$$h_{rc} = \frac{1}{\frac{1}{h'_{cv} + h'_r} + \frac{1}{h''_{cv} + h''_r}} \quad (28)$$

where T_{abs} is the temperature of the absorber.

The coefficient of exchange by natural convection inside the glass cubic box (absorber- glass) is given by the following correlation [14]:

$$h'_{cv} = 1.1 * (T_{abs} - T_v)^{1/4} \quad (29)$$

h'_r is the coefficient of loss by radiation between the absorber and the glass. It is expressed as

$$h'_r = \varepsilon_{av} \sigma (T_{abs}^2 + T_v^2) (T_{abs} + T_v) \quad (30)$$

T_v is the temperature of the glass

ε_{av} = Absorber - glass emissivity. It is expressed as:

$$\varepsilon_{av} = \frac{1}{\frac{1}{\varepsilon_a} + \frac{1}{\varepsilon_v} - 1} \quad (31)$$

With ε_a and ε_v respectively emissivity of the absorber and the glass.

The coefficient of loss by convection between the glass and the ambient air h''_{cv} is given by the following expressions [13]:

$$h''_{cv} = 7.5 + 4v \quad \text{for } 0 < v < 4 \text{ m/s} \quad (32)$$

or

$$h''_{cv} = 7.3 v^{0.80} \quad \text{for } 4 < v < 40 \text{ m/s} \quad (33)$$

where v is the wind speed (m/s).

The speed at the site was estimated at 2.5 m/s, average value in the city of Abidjan.

The radiation loss coefficient between the glass and the sky is written as:

$$h''_r = \varepsilon_v \cdot \sigma \cdot (T_v^2 + T_c^2)(T_v + T_c) \quad (34)$$

T_c is the temperature of the sky

The useful power Q_u is expressed as:

$$Q_u = Q_{abs} - P \quad (35)$$

Therefore, the global efficiency and the internal efficiency of the collector are given by the following relations:

$$\eta_g = \frac{Q_u}{Q_d} \quad (36)$$

where

$$Q_d = I_p C_g \rho A_{abs} \quad (37)$$

$$\eta_i = \frac{Q_u}{Q_{abs}} \quad (38)$$

It should be noted that we just measured the global solar radiation. As for I_p , the direct component of solar radiation, it was obtained from a mathematical model which was studied and compatible with our experimental site [15].

Table 1 gives the results of the efficiency calculations for the ellipsoidal concentrator.

Table 1. Efficiencies obtained with the ellipsoidal concentrator solar cooker.

Ellipsoidal Concentrator							
Cooking day	Average direct solar radiation (W/m ²)	Average absorbed power (W)	Average power lost (W)	Average useful power (W)	Average global loss Coefficient (W/m ² .°C)	Internal efficiency %	Global efficiency %
25/10/2017 (07 eggs) 10:40-11:30	769,41	702,67	37,83	664,84	9,85	94,62	76,40
25/10/2017 (250g rice) 11:50-13:10	805,71	735,82	64,14	671,69	10,24	91,28	73,71

Table 2 gives the results of the efficiency calculations for the parabolic concentrator.

Table 2. Efficiencies obtained with the parabolic concentrator solar cooker.

Parabolic Concentrator							
Cooking day	Average direct solar radiation (W/m ²)	Average absorbed power (W)	Average power lost (W)	Average useful power (W)	Average global loss Coefficient (W/m ² .°C)	Internal efficiency %	Global efficiency 1%
25/10/2017 (07 eggs) 10:40-11:30	769,41	702,67	44,12	658,55	9,90	93,72	75,68
25/10/2017 (250g riz) 11:50-13:10	805,71	735,82	75,26	660,56	10,59	89,77	72,49

Tables 1 and 2 show that the ellipsoidal concentrator solar cooker and the parabolic concentrator solar cooker have almost the same efficiency, with a slight advantage for the ellipsoidal concentrator solar cooker.

5. Conclusion

A solar cooker has been designed with an ellipsoidal concentrator, by using one the two focal points of the ellipse. In a first step, the reflective surface was a galvanized steel sheet. In the experimental study, two configurations were tested: experimentation with and without glass cubic box. In the configuration with glass cubic box, six (6) eggs were completely cooked after 80 minutes of cooking. In the second step, the reflective surface was coated with mirror. In such configuration, 07 eggs were perfectly cooked after 40 minutes of cooking in 0.5 litres of water. Then 250 grams of rice were also cooked after 80 minutes of cooking, in 0.5 litres of water. The study showed that the ellipsoidal concentrator is efficient and well suitable for solar cooking.

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