# Comparative performance of two parabolic solar cookers: influence of a glass cubic box

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## Abstract:

This work consists of experimentally comparing the performance of two parabolic solar cookers with the same opening diameter and the same galvanized sheet coating. The first cooker called $CSP_1$ and the second cooker $CSP_2$ have respectively the focus located below and above the plane of opening of the paraboloid. A first series of cooking tests was carried out with both prototypes. The overall loss coefficient obtained on each absorber was 13.64 W / $m^2$.°C for $CSP_1$ and 24.03 W / $m^2$.°C for $CSP_2$. This shows that energy losses by convection and radiation are high with $CSP_2$. The cooking was only perfect with $CSP_1$. In order to improve the performance of $CSP_2$, a glass cubic box around the pan was associated. Thus, a second series of cooking tests was carried out. The overall loss coefficient has been 14.98 W / $m^2$.°C with $CSP_1$ and 8.48 W / $m^2$.°C with $CSP_2$. This reflects the improved performance of $CSP_2$ by introducing the glass cubic box. Favorable temperatures for cooking food (rice and eggs) were obtained with the two parabolic solar cookers.

**Keywords**: Parabolic solar cooker, galvanized sheet, focus, glass cubic box, performance.

## 1-Introduction

In Côte d'Ivoire, like in most developing countries, wood energy is widely used for cooking. Its share in the overall satisfaction of energy needs is estimated at around 76% (in 2008) [1]. The domestic use of vegetation cover (firewood, charcoal, etc ...) and the extraction of wood fuel increases with population growth. This is one of the major causes of deforestation. The supply of wood and charcoal is also becoming more and more difficult and expensive. This is linked to a galloping desertification. To overcome these problems, one of the natural and easy alternative is obviously the use of solar energy. Côte d'Ivoire has an enormous solar potential characterized by a daily average radiation varying between 3 and 5 kWh / m² depending on the region and a sunshine duration of 6H [1]. This free, non-polluting energy can be converted into useful energy for cooking by collectors such as parabolic solar concentrators.

Many studies have been done on these solar cookers. Various configurations exist with respect to the paraboloid opening plane. We call $CSP_1$ and $CSP_2$ the respective configuration whose focal point is located below and above the paraboloid opening plan. Gavisiddesha et al [2] have designed and studied the performance of a $CSP_1$ type with a focal length of 0.30m and a depth of 0.40m. As for A. R. El Ouederni et al [3], they have constructed a type of $CSP_2$ with a focal length of 0.75 m and a depth of 0.4 m. Similarly I. Zeghib et al [4] built another $CSP_2$ type with focal length of 0.894 m and a depth of 0.080 m. The prototype built by I. Ladam Mohammed [5] has a focal length of 0.698 m and a depth of 0.29 m.

Our work consists firstly, to carry out an experimental comparative study of these two cookers $CSP_1$ and $CSP_2$ and then, to evaluate the effect of a glass cubic box on the performance of $CSP_2$.

## 2-Realization and description of the prototypes

**Table 1** shows some characteristics of the two parabolic solar cookers designed in the Solar Energy Laboratory (L.E.S) of Felix Houphouët Boigny Cocody University, Abidjan. The reflective facets are galvanized steel sheet whose thickness is 0.8 mm.

**Table 1: Characteristics of the two prototypes**

| Cooker | Opening diameter (m) | Focal length (m) | Depth of parabola (m) | Number of facets |
|---|---|---|---|---|
| **$CSP_1$** | 1.2 | 0.18 | 0.5 | 18 |
| **$CSP_2$** | 1.2 | 1.0 | 0.09 | 6 |

Two experiments were carried out as shown in **Figure 1** where $CSP_2$ is without a glass cubic box and **Figure 2** where $CSP_2$ has a glass cubic box. Black painted receptors or pans are perched on a beam and held by a collar. In this position, the base of the pan is held at a distance from the focal point called the back axial distance L of the focal point as shown in **Figure 3**. Thus, the lateral face and the base of the pan are flooded by the reflected rays emanating from the paraboloid. The following relationship, allows the calculation of this back axial distance L:

$$d_2 = \frac{L \cdot d}{f - h} \qquad (1)$$

Where $d_2$ is the diameter of the pan, f the focal length, h and d respectively the height and the opening diameter of the parabola. Each paraboloid is secured to a manual tracking system of the sun, which ensures its stability and the orientation of the opening according to the height of the sun. In order to limit the losses by convection and radiation on the absorber and create a greenhouse effect, a glass cubic box was introduced into $CSP_2$. It wraps up the focus and the pan of the cooker.


**Figure 1: Experimental device where $CSP_2$ is without glass cubic box.**


**Figure 2: Experimental device where $CSP_2$ is provided with a glass cubic box.**

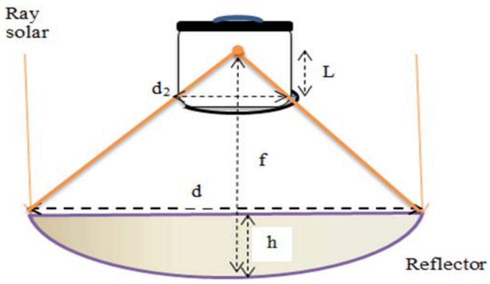


**Figure 3**: **Back axial distance L of the focal point**

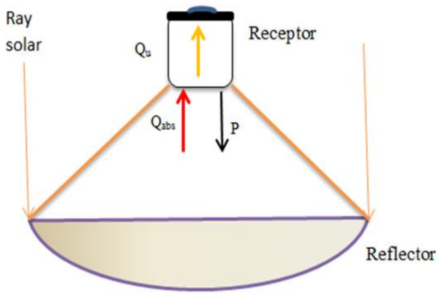


**Figure 4 : Energy balance of the absorber.**

The performance indicators that have been defined in this paper are the overall loss coefficient and the efficiency. For that, we have to evaluate the heat balance.

## 3- Thermal balance

### 3.1. Energy balance of the receiver without glass cubic box

If $Q_u$ is the useful power received by the receiver, it is given by the difference between the absorbed power $Q_{abs}$ and the losses P. The thermal balance on the absorber is shown in **Figure 4**.

$Q_{abs}$ is expressed by [6]:

$$Q_{abs} = \eta_0 I_p C_g \rho \gamma A_{abs} \tag{2}$$

$\eta_0 = \alpha\tau$ is the optical efficiency,

$\alpha$ = Receiver absorption coefficient

$\tau$ = Transmission coefficient of the glazing (if any)

$I_p$ = Direct irradiance of the radiation (W / m$^2$)

$\rho$ = Reflection coefficient of the parabolic reflector

$\gamma$ = Intercept coefficient expressed as [6]:

$$\gamma = 1 - \exp\left(-820\left(0.7 \cdot \frac{r}{f}\right)^2 (1 + \cos\phi)\right) \quad (3)$$

Where $\phi$ is the opening angle of the parabola in degrees.
r designating the exergy is governed by Eq.(4) [7]:

$$r = 1367 * \pi * \left(\frac{d}{2}\right)^2 * \left(1 - \frac{Ti}{T}\right) \quad (4)$$

With
$Ti$ = Initial temperature of the pan (°C)
$T$ = Final temperature of the pan (°C)
$A_{abs}$ = Total surface receptor that is expressed by:

$$A_{abs} = \pi \cdot \frac{d_2^2}{4} + \pi \cdot d_2 \cdot h_{abs} \quad (5)$$

With:
$d_2$ = Receiver opening diameter
$h_{abs}$ = Receiver height
Eq. (2) can be rewritten as follows:

$$Q_{abs} = A_{abs} . P_{abs} \quad (6)$$

With

$$P_{abs} = \eta_0 \cdot I_p \cdot C_g \cdot \rho \cdot \gamma \quad (7)$$

$$C_g = A_{op}/A_{bs} \quad (8)$$

$C_g$ is the geometric concentration coefficient of the concentrator, with
$A_{op}$ = Aperture area of the collector
Losses P are expressed by:

$$P = P_{cv} + P_r \quad (9)$$

$P_{cv,}$ the loss by convection is written:

$$P_{cv} = h_{cv} \cdot A_{abs} . (T_{abs} - T_a) \quad (10)$$

Where $h_{cv}$ is the coefficient of loss by convection.
$P_r$, the loss by radiation is written:

$$P_r = h_r \cdot A_{abs} \cdot (T_{abs} - T_c) \quad (11)$$

Where $h_r$ is the coefficient of loss by radiation.
If we assume that the temperature of the sky $T_c$ is (by approximation) equal to $T_a$ the ambient temperature, we have:

$$P_r = h_r \cdot A_{abs} \cdot (T_{abs} - T_a) \quad (12)$$

Equation Eq. (9) becomes:

$$P = h_{cv} \cdot A_{abs} \cdot (T_{abs} - T_a) + h_r \cdot A_{abs} \cdot (T_{abs} - T_a) \quad (13)$$

The coefficient of loss by convection $h_{cv}$ is given for the temperature ranges by the following expressions [8]:
$100\ °C < T_{abs} < 500\ °C$

$$h_{cv} = 7.5 + 4v \quad (0 < v < 4\ m/s) \quad (14)$$

or

$$h_{cv} = 7.3\, v^{0,80} \qquad (4 < v < 40\ m/s) \tag{15}$$

With v the wind speed (m / s).
The speed at the site was estimated at 2.5 m / s, average value in the city of Abidjan [9].
The radiation loss coefficient is written:

$$h_r = \varepsilon \cdot \sigma \cdot \;\; T_{abs}^2 + T_a^2 \;\;\; T_{abs} + T_a \tag{16}$$

Finally we can write:

$$P = A_{abs} \cdot (h_{cv+}h_r) \cdot \;\; T_{abs} - T_a \tag{17}$$

We deduce the useful power $Q_u$:

$$Q_u = Q_{abs} - P \tag{18}$$

$$Q_u = A_{abs} \cdot \; P_{abs} - A_{abs} \cdot (h_{cv+}h_r) \;\; T_{abs} - T_a \tag{19}$$

$$Q_u = A_{abs} \;\; P_{abs} - (h_{cv+}h_r) \;\; T_{abs} - T_a \tag{20}$$

## 3.2. Energy balance of the receiver with glass cubic box

The powers absorbed and useful are determined respectively from the eq. (2) and eq. (18).
The cubic glass enclosure envelops the absorber of the solar parabolic cooker. The greenhouse effect is then generated. In this case the coefficients by radiation and convection appear inside and outside of the glass cubic box.

• **Inside the glass**: - the coefficient of exchange by radiation between the absorber and the glass is written [8]:

$$h'_r = \varepsilon_{av}\sigma(T_{abs}^2 + T_v^2)(T_{abs} + T_v) \tag{21}$$

Where:
$\varepsilon_{av}$ = Absorber - glass emissivity. It is governed by the relation [8]:

$$\varepsilon_{av} = \frac{1}{\frac{1}{\varepsilon_a} + \frac{1}{\varepsilon_v} - 1} \tag{22}$$

With $\varepsilon_a$ and $\varepsilon_v$ respectively emissivity of the absorber and the glass.
The coefficient of exchange by natural convection inside the glass cubic box (absorber- glass) is given by the correlation eq. (23) [8]:

$$h'_{cv} = 1.1 * (T_{abs} - T_v)^{1/4} \tag{23}$$

$T_v$= Temperature of the glass we assume uniform.

- **outside the glass:** - the coefficient of exchange by radiation between the glass and the sky is written:

$$h''_r = \varepsilon_v\sigma(T_v^2 + T_c^2)(T_v + T_c) \tag{24}$$

The coefficient of exchange by convection between the glass and the ambient is given by the correlation (14).
The resulting coefficient of exchange is given by the following expression [8]:

$$h_{rc} = \frac{1}{\frac{1}{h'_{cv} + h'_r} + \frac{1}{h''_{cv} + h''_r}} \tag{25}$$

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

$$\eta_g = \frac{Q_u}{Q_d} \tag{26}$$

Where $Q_d = I_p C_g \rho A_{abs}$

$$\eta_i = \frac{Q_u}{Q_{abs}} \tag{27}$$

We indicate that the direct component of solar radiation was obtained from a mathematical model which was studied and compatible with our experimental site [10].

## 4- **Discussion and analysis of experimental results**

During the cooking tests, measured variables were the overall irradiance using a pyranometer and temperatures (of the cooking, the ambient air, the bottom of the pan and also the inside and outside of the glass cubic box) using platinum resistance thermometers. The maximum duration of cooking for the two foods (eggs and rice) was 2 hours, in accordance with "Solar cookers international" [11]. Simple solar cookers used in the normal conditions, reach temperatures ranging from 82 ° C to 121 ° C or even more. Then the food start to cook between 82 ° C and 91 ° C, which is adequate but not enough to burn or lose their nutrients. The tests were carried out on the roof of the solar energy laboratory building in Abidjan (Côte d'Ivoire).

• **Test carried out without glass cubic box**, on 14/03/2017: This test concerned the cooking of 04 eggs in 0.5 L of water. **Figure 5** shows the evolution curves of the irradiance and cooking and ambient air temperatures versus time for $CSP_1$ and $CSP_2$.

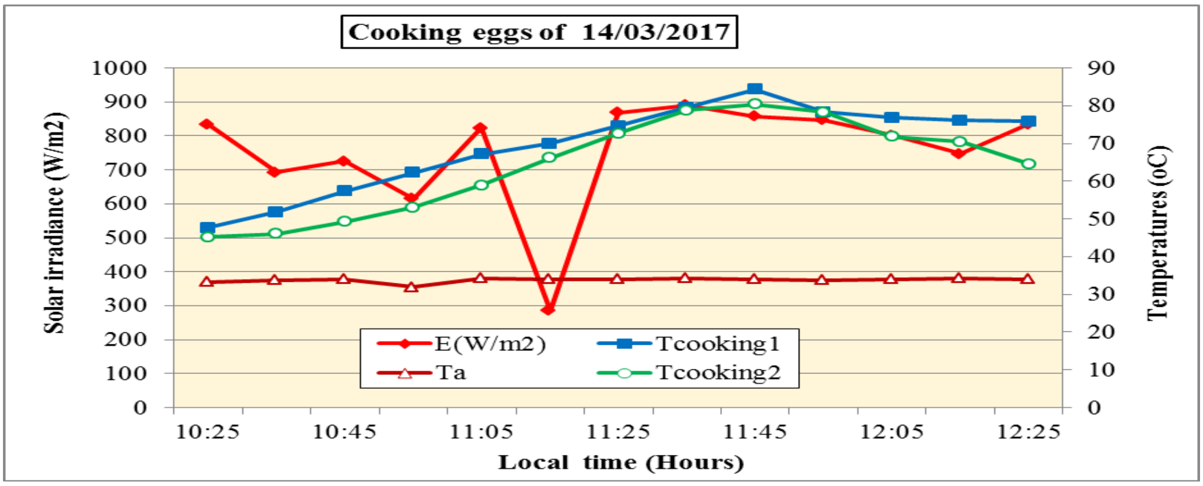


**Figure 5: Evolution curves of irradiance and temperatures versus time.**

In **Figure 5**, E is the solar irradiance, Tcooking is ths cooking temperature ($^o$C) and Ta is the ambient temperature ($^o$C).

In **Table 2**, are consigned the results of cooking test for 04 eggs in 0.5 L of water carried for $CSP_1$ and $CSP_2$ without glass cubic box.

**Table 2: Results of the test performed on the 14/03/2017**

| | Direct Average irradiance ($W/m^2$) | Duration cooking | Max (Tcooking) ($^oC$) | Overall loss coefficient ($W/m^2.^oC$) | Overall efficiency % | Cooking state of eggs |
|---|---|---|---|---|---|---|
| $CSP_1$ | 755.71 | 10:25 - 12:25 | **84.3** at 11:15 | 13.64 | 74.34 | Total |
| $CSP_2$ | | | **80.4** at 11:15 | 24.03 | 71.46 | partiel |

In that configuration, $CSP_1$ has a higher performance than $CSP_2$. Therefore we introduced a glass cubic box, with dimensions 0.35 m x 0.35 m x 0.35 m in $CSP_2$.

- **Tests carried out with glass cubic box on $CSP_2$ and no glass box on $CSP_1$**

These tests involved the cooking of 05 eggs in 0.5 L of water for the days of April 15$^{th}$ and 16t$^{h}$, 2017 and the day of April 17$^{th}$, 2017 for cooking of fat rice with 03 eggs in each pan. The results are shown in **Table 3**.

**Table 3: Results of tests carried out with glass cubic box on $CSP_2$**

| | Day | Direct Average irradiance ($W/m^2$) | Duration cooking | Max (Tcooking) ($^oC$) | Overall loss coefficient ($W/m^2.^oC$) | Overall efficiency % | Cooking state of eggs and rice |
|---|---|---|---|---|---|---|---|
| $CSP_1$ | **15/03/17** | 648.66 | 10:20-12:20 | **87.0** at 12:20 | **14.11** | 72.23 | **Total** |
| $CSP_2$ | | | | **100.0** at 11:10 | **8.11** | 75.31 | |
| $CSP_1$ | **16/03/17** | 957.11 | 12:25-13:25 | **87.0** at 13:25 | **13.59** | 75.58 | |
| $CSP_2$ | | | | **100.0** at 13:15 | **7.98** | 77.27 | |
| $CSP_1$ | **17/03/17** | 900.38 | 11:35-13:35 | **98.4** at 13:05 | **14.98** | 72.53 | |
| $CSP_2$ | | | | **100.6** at12:35 | **8.48** | 75.67 | |

In **Figures 6**, **7** and **8** are shown the evolution curves of temperature and irradiance versus time.

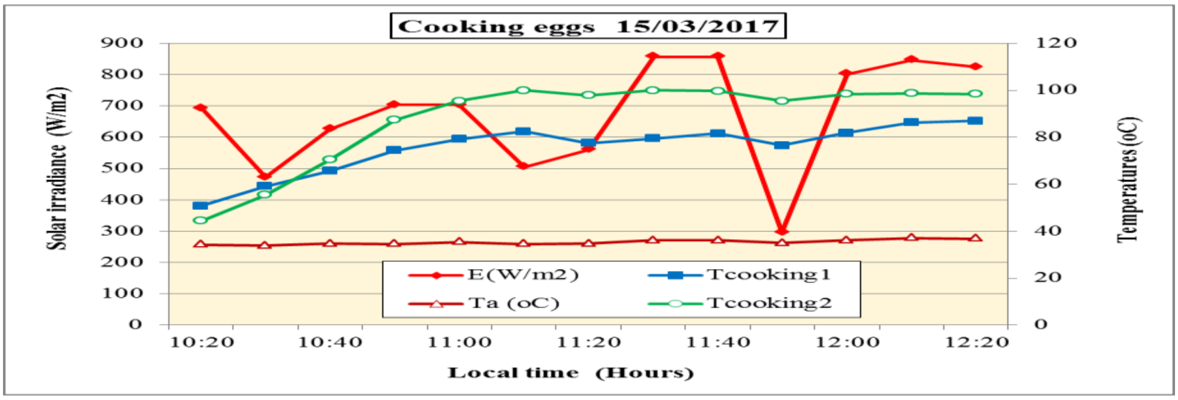


**Figure 6: Evolution curves of irradiance and temperatures versus time.**

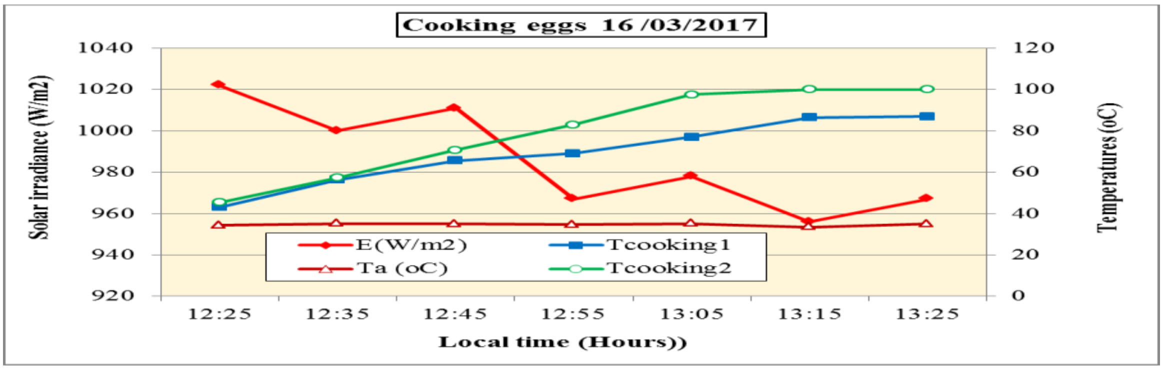


**Figure 7: Evolution curves of irradiance and temperatures versus time.**

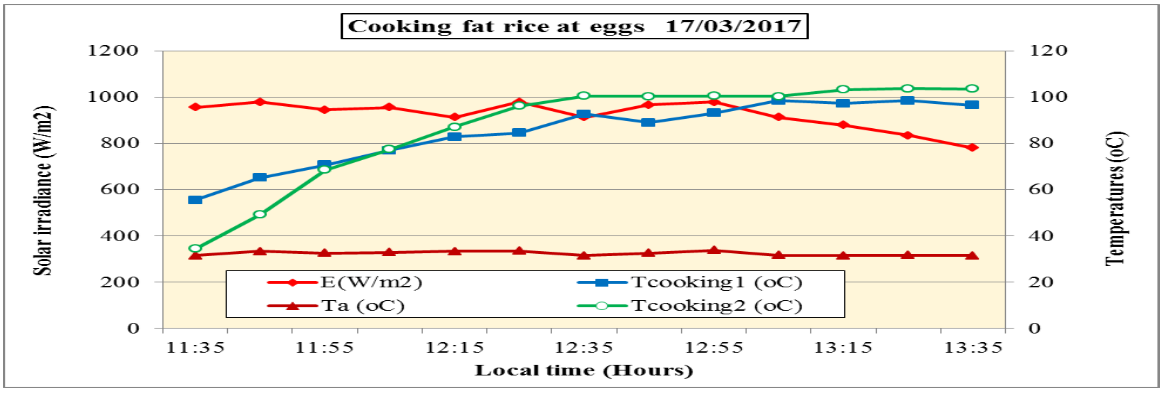


**Figure 8: Evolution curves of irradiance and temperatures versus time.**

The results of the tests carried out when $CSP_2$ has a glass cubic box show well the improvement to its performance. The eggs were completely cooked during the days of March 15$^{th}$ and 16$^{th}$ 2017. On the day of March 17$^{th}$ 2017, **Figures 9** and **10** demonstrate the perfect cooking state of fat rice at eggs and the formation of more cheese topping in the pan of $CSP_2$ than on that of $CSP_1$. The Cooking of fat rice at eggs was total.


**Figure 9 : A) Cooking state in CSP1 (B) and Cooking state in CSP2**


**Figure 10: Cheese topping formed during cooking with (A) CSP1 and (B) CSP2.**

**5- Conclusion:** In the climatic conditions of Abidjan, cooking with our parbolic solar cookers are attainable. Furthermore, the results obtained show that the introduction of the glass cubic box reduces the losses on the absorber and considerably improves the performance of the parabolic solar cooker.

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