

Design and evaluation of a conical solar cooker in glazed and non-glazed configurations: Cooking tests

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Abstract. This paper reports the evaluation of a conical solar cooker. This prototype was designed in galvanized sheet with an opening diameter of 120 cm. The experiment was carried out on the roof of the building of the solar energy laboratory of FHB University. Tests of boiling eggs were carried out. During operation, two configurations of the conical cooker were adopted. In the first configuration, the cooker was used without modification. On the other hand, in the second configuration, a removable glass plate is placed in the cone and at a distance of 25 cm from the base. This contribution has the role of creating a greenhouse effect between the absorber and the glass. During the tests, the temperature of cooking, the ambient temperature as well as the solar illumination were measured. The tests were conducted in accordance with the maximum cooking time of some foods given by "Solar cookers international". Despite the observed cloudy periods, maximum temperatures obtained by the eggs were 82 °C in 2 hours cooking for the first configuration and 100 °C in cooking 1h10 for the second configuration. These results show that the addition of the glass plate in the conical solar cooker gives good satisfaction. In addition, in both cases, a perfect cooking of the eggs was observed.

1. Introduction

There is a need for cooking, everywhere in the world, in urban as well as in rural areas. So far, in developing countries, the energy requirements for cooking depend mainly upon conventional energy sources, such as firewood and coal. In urban areas, LPG is also used for cooking, as well as electricity. The collection of wood from forests is responsible for deforestation and other environmental damages. Solar energy is an alternative power source, which is clean, renewable and sustainable.

Therefore, several types of solar cookers have been developed. Several concentration systems of solar energy are used to reach high temperatures which are required for cooking. The paraboloid concentrator solar cooker is one of them. This type of solar cooker has been studied by several researchers [1-7]. Another type is the Pipe cooker [8]. This cooker is fitted with an oil filled pipe, which is connected to a cooking box. The hot box cooker is another type, which has been studied by several researchers [8,9]. Our paper is about the conical solar cooker. Some studies have been made about this type [10-12]. It has a conical concentrator. Sharaf E [10] has designed a conical solar cooker that concentrated solar radiation at the bottom end of the cone. Some characteristic parameters of one of his cookers are the following: apex angle $\theta = 30^\circ$; radius of the focus $R_2 = 14$ cm; radius of opening $R_1 = 38.24$ cm; length of the reflective part $l = 93.68$ cm; height of the reflective part $h = 90.49$ cm. He carried out some tests of boiling water to 100 °C. He also performed tests of cooking chickens and red



meat.

Kerdchang P and Puangsombur W [11] built a conical solar cooker. Its type is the same as the one designed by Sharaf E [10] with the following characteristic parameters: apex angle $\theta = 45^\circ$; radius of the focus $R_2 = 15$ cm; radius of opening $R_1 = 36.2$ cm; length of the reflective part $l = 55.4$ cm; the height of the cone is 87.4 cm. They performed cooking test of rice, eggs and pork without tracking of the sun. Mahdi K and Bellel N [12] made a study and a theoretical simulation of a conical solar collector for steam generation. The conical concentrator has a vertex angle equal to 90° and a cylindrical axial receiver. The theoretical study showed that the absorber can reach a temperature higher than 200°C .

In the present, a conical solar cooker is designed, built and experimented. It is the same type as the one designed by Sharaf E [10], but in the prototype built, the radius of opening R_1 is increased, in order to increase the solar radiation collected by the conical concentrator. As a consequence, the length of the reflecting part was increased. The reflecting conical surface is in galvanized steel. The conical solar cooking system is fitted with a manual tracking system, for the follow-up of the sun. Every 20 minutes, the conical concentrator is oriented in front of sun. The absorber is set at the bottom end of the cone and insulated. The experiments were carried out with and without a circular glazing installed in the cone above the absorber.

2. Design and description of the conical concentrator

2.1. Design

The design parameters of the conical concentrator are shown in figure 1, which is a cross-section of the reflective part of the cone. The cone is truncated along CC' which is the bottom and focus of the concentrator. Hence, the reflective frustum is a conical flask which is in galvanized steel. The absorber is located at the bottom of the conical concentrator.

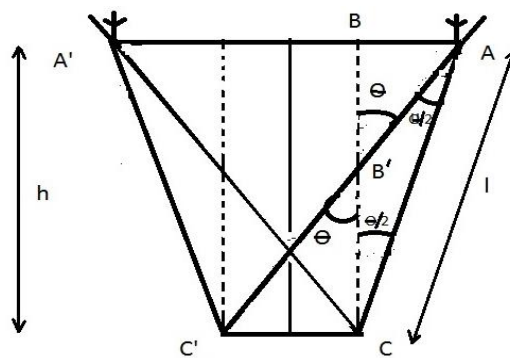


Figure 1. Cross-section of the conical concentrator.

As shown in figure 1, θ is the apex angle of the concentrator; $CC' = 2R_2$ is the diameter of the focus; $AA' = 2R_1$ is the diameter of the opening. Let us call A the opening area and S the focus area of the concentrator. Then the geometric concentration C is expressed as

$$C = \frac{A}{S} = \frac{\pi R_1^2}{\pi R_2^2} = \frac{R_1^2}{R_2^2} \quad (1)$$

From triangle $C'B'C$, one gets

$$\frac{C'C}{B'C} = \tan\theta \quad (2)$$

Triangle $CB'A$ shows that $CB' = B'A$

Then from equation (2), one gets

$$\frac{C'C}{B'A} = \frac{2R_2}{B'A} = \tan\theta \quad (3)$$

Considering triangle BB'A, one gets

$$\frac{BA}{B'A} = \frac{R_1 - R_2}{B'A} = \sin\theta \quad (4)$$

From equations (3) and (4), the following equation is obtained

$$R_1 = R_2(2\cos\theta + 1) \quad (5)$$

Combining equations (5) and (1), one gets

$$C = (2\cos\theta + 1)^2 \quad (6)$$

The length l and the height h of the reflective part are obtained by considering triangle ABC. Since $l = AC$ and $h = BC$, one gets

$$\frac{AB}{AC} = \frac{R_1 - R_2}{l} = \sin\frac{\theta}{2} \quad (7)$$

$$\frac{AB}{BC} = \frac{R_1 - R_2}{h} = \tan\frac{\theta}{2} \quad (8)$$

2.2. Description

The conical concentrator was built with the following dimensions: apex angle $\theta = 30^\circ$; radius of opening $R_1 = 40.99$ cm; radius of the focus $R_2 = 15$ cm; length of the reflective part $l = 100.46$ cm; height of the reflective part $h = 97.03$ cm. The geometrical concentration calculated by using equation (6) is $C = 7.46$.

Figure 2 shows a section of the conical solar cooker studied. The frame of the cone is a sheet of galvanized steel. The reflective inner surface of the cone is the surface of the galvanized sheet. The bottom of the cone is embedded in a circular vase in stainless steel painted black, called absorber. Thermal insulation of the absorber is ensured by wood, plywood, polystyrene and a thin layer of plaster. Some steel rods hold the cone.

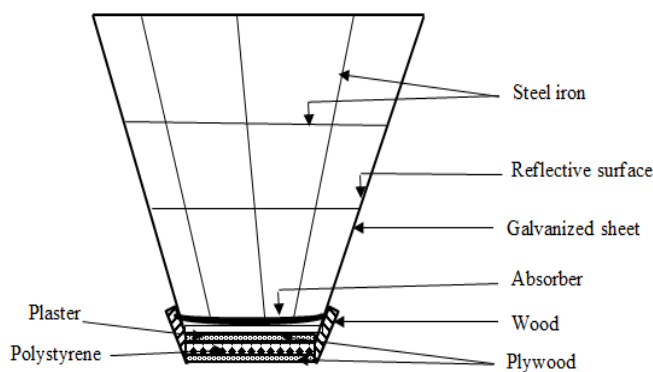


Figure 2. Schematic representation of the conical cooker.



Figure 3. Circular glass cover.

The device thus represented is the non-glazed configuration. When the glass circular plate illustrated in figure 3 is placed in the cone 25 cm above the absorber, we have the glazed configuration. In this case, a greenhouse effect is created in the cone and an energy gain is observed.

The prototype is mounted on a support as shown in figure 4. The frame of the cone is fitted with a manual slider that guides the opening of the cone parallel to the solar radiation and stabilizes the cone. Figure 4 shows an overall view of the cooker with the accessories on the test site.



Figure 4. Overall view of the conical solar cooker with accessories on the experimentation site.

In operation, the solar rays falling parallel to the opening are reflected towards the bottom of the cone, as shown in figure 5. In the non-glazed configuration, the operating principle relies on two conjugate effects:

- The concentration of the incident solar rays reflected by the inner surface of the cone towards the absorber,
- The effect of the black body due to the absorber.

In its glazed configuration, the greenhouse effect is added by the insertion of the glass plate.

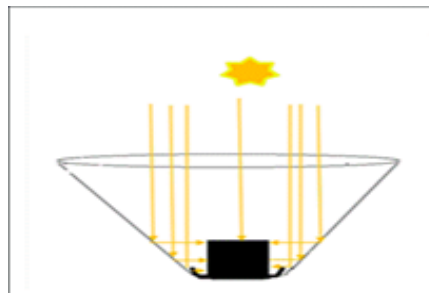


Figure 5. Solar radiation on the absorber in the cone.

3. Experimental study

The experimental tests were carried out on the roof of the Solar Energy Laboratory of the University Felix Houphouët Boigny.

These tests were carried out on November 8th, 2016 and on December 3th, 2016. The measured quantities were the temperatures (ambient, cooking) and the total solar radiation incident on a horizontal plane. The temperatures were measured by using platinum resistance thermometers. Using a manual switch, data was recorded at a time interval of 10 min. An Eppley-type pyranometer (precision $\pm 10 \text{ W / m}^2$) was used to record global solar radiation values.

Authors such as Adel M A *et al* [13], Sambo *et al* [14] cited by Adegoke [15] used the cooking duration and the efficiency, as parameters to evaluate the performance of the solar cooker. For cooking time, "Solar Cookers International" [16] has established approximate cooking times in sunny weather.

According to [16], perfectly cooking of rice, eggs, etc ..., requires a cooking duration of 2 hours. In addition, simple solar cookers, used under normal conditions, reach temperatures ranging from 82 °C to 121 °C or higher. Food starts to cook for temperatures between 82 °C and 91 °C, which are enough but not enough to burn or lose nutrients.

Regarding the efficiency of the solar cooker, the following expression is used [15]:

$$\eta_c = \frac{(m_p C_p + m_w C_w)(\bar{T}_w - \bar{T}_a)}{A_c I_G t} \quad (9)$$

where m_p and m_w represent mass of the pan and water respectively; C_p and C_w represent specific heat capacity of the pan (920 J / kg.°C) and the water (4200 J / kg.°C) respectively; T_w and T_a stand for average water and ambient temperatures respectively (°C); A_c refers to the area of the solar collector (m²); I_G represents the average value of the intensity of the overall irradiation (W/m²); t = Cooking time.

4. Results and discussion

Among the experiments carried out, two days of tests were chosen, namely November 8th and December 3th 2016. The average irradiance for those two days was 568 W / m² for November 8th 2016 and 644 W / m² for December 3th 2016. The tests consisted in boiling eggs in a pan painted black. During the first day, the conical stove operated in its unglazed configuration with 0.5 L of water and 5 eggs in the pan. On the second day, the conical stove operated in its glazed configuration with 0.5 L of water and 10 eggs in the pan. During these tests, maximum duration set was 2 hours.

Figures 6 and 7 show the temporal variations of solar irradiance, temperature of cooking and temperature of the ambient air versus time for November 8th and December 3th 2016 respectively.

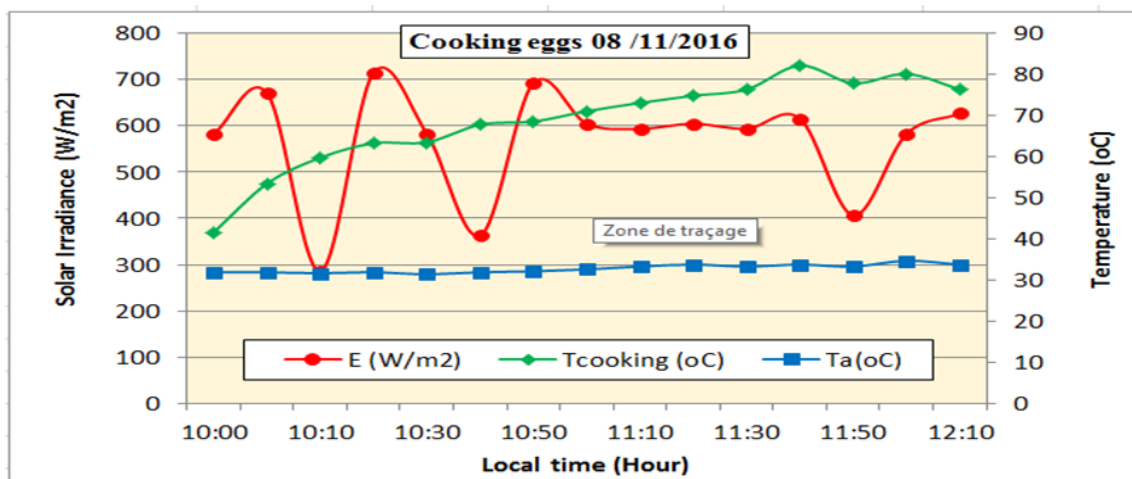


Figure 6. Temporal evolution curves of irradiance, ambient air and cooking temperatures, 08/11/2016.

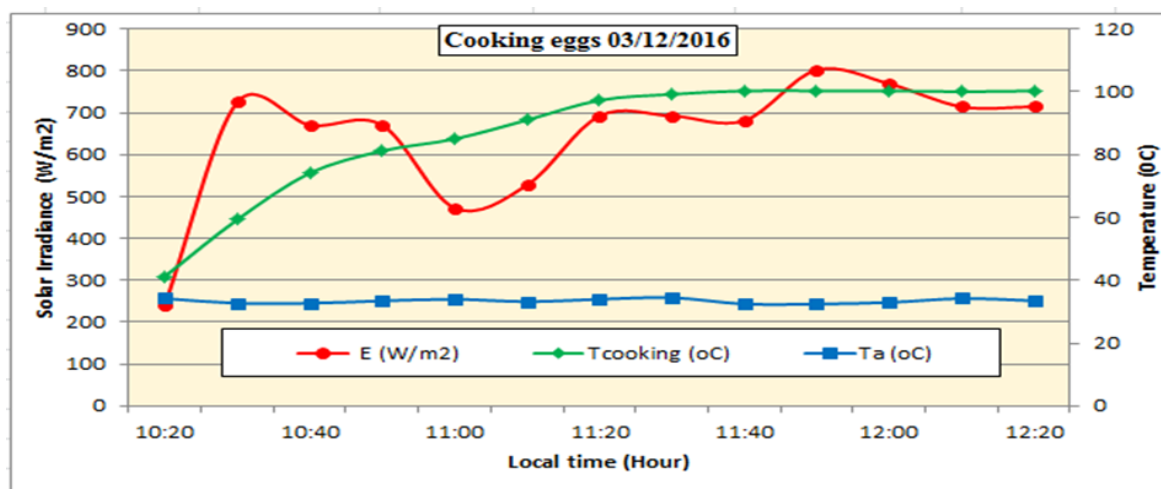


Figure 7. Temporal evolution curves of irradiance, ambient air and cooking temperatures, 03/12/2016.

In figures 6 and 7, E (W/m^2) is the solar irradiance; T_{cooking} ($^{\circ}\text{C}$) is the temperature of cooking; T_a ($^{\circ}\text{C}$) is the ambient temperature.

It should be noted that, at both configurations (glazed and non-glazed), a cloudy period lies approximately from 10:0 to 11:0. For the non-glazed configuration, another cloud passage is observed at 11:50.

So, the tests were carried out under intermittent cloud passages that are observed on the curves of solar irradiance by fluctuations. Despite this bad weather, the results show that cooking is achievable with both configurations of our conical solar cooker.

In the non-glazed configuration, the temperature of 82°C is reached in 2 hours of cooking the 5 eggs.

In the glazed configuration, this temperature of 82°C is reached within 40 minutes of cooking and the temperature of 100°C is reached within 70 min of cooking the 10 eggs. During these tests, the eggs were perfectly cooked despite intermittent cloud cover. So the insertion of the circular glass plate brings an energy gain in our conical solar cooker and accelerates the cooking of food.

Moreover, the influence of the cloud passages is more felt in the non-glazed configuration than in the glazed configuration. That seems logical because the presence of the glass reduces convection and radiation losses and promotes a gain of energy [17].

The determination of cooking efficiency gave 58 % for the non-glazed configuration and 70.89 % for the glazed configuration. These results show that the performance under glazed configuration is better in comparison to the non-glazed configuration.

- If compared with other solar cookers, the conical type as some advantages:
- It has a small opening area (0.53 m^2 in our case)
- The maximum time for cooking is shorter. In our case, 10 eggs were cooked in 70 minutes.

This cooking time will be made shorter when the reflective surface will be coated with mirror to make it more reflective.

5. Conclusion

In this work, a solar cooker was designed and built with the conical reflector in galvanized steel. The conical solar cooker was experienced in local climatic conditions. Two configurations of the solar cooker were tested and compared during cooking tests of eggs. The results showed that inserting a circular plate into the cone improved the performance of the prototype. Furthermore the cooking tests were carried out in conventional cooking durations given by "Solar Cookers International" [16].

Appendix

Nomenclature

| | |
|-------|---|
| A_C | Area of the cooker (m^2) |
| C | Geometrical concentration |
| C_p | Specific heat of the pan ($\text{J/kg} \cdot ^{\circ}\text{C}$) |
| C_w | Specific heat of the water ($\text{J/kg} \cdot ^{\circ}\text{C}$) |
| h | Height of the reflective part (cm) |
| I_G | Overall irradiation (W/m^2) |
| l | Length of the reflective part (cm) |
| m_p | Mass of the pan (kg) |
| m_w | Mass of the water (kg) |
| R_1 | Radius of opening (cm) |
| R_2 | Radius of the focus (cm) |
| T_a | Ambient temperature ($^{\circ}\text{C}$) |
| T_w | Temperature of the pan ($^{\circ}\text{C}$) |
| t | Cooking time (s) |

Greek letters

| | |
|----------|------------|
| θ | Apex angle |
|----------|------------|

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