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Theoretical and Experimental Studies of a Box-Type Solar Cooker in Unfavorable Climatic Conditions

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Abstract

A box-type solar cooker with an inclined surface, equipped with a concentration reflector to allow maximum energy to be collected, enabled cooking tests to be carried out in the rainy season. Different thermocouples were implanted on various places of the cooker. The temperature measurements from these sensors were taken every 10 minutes. The tests presented in this article relate to the preparation of eggs and rice. The absorber temperatures during the tests exceeded 100˚C. The cooking times were between 1 h 50 min and 2 h 20 min despite the numerous cloudy periods. The cooker made it possible to reach sufficient temperatures for healthy cooking of food. The results obtained for these first tests are satisfactory and very encouraging.

Keywords

Solar Radiation, Box-Type Solar Cooker, Energy, Inclined Aperture Area

1. Introduction

South Saharan countries have large areas whose needs for cooking food are closely linked to the harvesting of wood and natural gas (fossil). In Côte d'Ivoire, charcoal and fuelwood predominate even if gas is also used. Its share in the overall satisfaction of energy needs is estimated at around 76% in 2008 [1]. These farms are gradually increasing, worsening the problem of the scarcity of these resources and causing their exhaustion over the years. These energies are also at the root of environmental pollution and global warming [2]. The exhaustion of the sources of these energies, their harmful consequences linked to their use on the environment and the increase in energy needs in the world led the countries to be interested in other types of energies: renewable energies [3]. These energies are silent and little polluting. Solar energy is one of these energies. It is a promising option capable of being one of the main sources of energy in the domestic sector [4] [5]. Solar cooking is one of these possible applications. This application is a real solution to limit deforestation, pollution and the abusive use of fossil fuels [6]. Each solar cooker can save one tonne of wood per year in sunny, but arid regions and can therefore avoid the release of a large amount of greenhouse gases [7] [8].

A solar cooker is a technology that can provide heat in a natural and renewable way, for cooking through the technique of concentrating the sun's rays. The use of this technology opens up new perspectives and makes it possible to preserve current reserves.

The objective of this work is to make an experimental study of this technology in unfavorable climatic conditions (rainy season). A validation of the results obtained from the cooking system carried out by comparison with various achievements around the world is envisaged.

2. Description of the Box-Type Solar Cooker

The cooker is mainly made from plywood sheets, flat mirrors and an absorber made of blackened 0.8 mm thick galvanized sheet metal. With this type of system, we seek to raise the temperature of the metal plate that will support the kitchen utensil when it is exposed to solar radiation. For this, we place the metal plate in a thermally insulated box on the rear part with a layer of glass wool carefully wrapped in aluminum foil.

In the internal volume of the box, four mirrors are placed, each fixed on one side of the box and inclined by 65˚ relative to the bottom of the box, so that it can reflect all of the incident solar radiation passing through the opening surface of the box towards the absorber. To create the greenhouse effect and minimize heat loss from the hot plate to the environment, there is a transparent cover 10 mm thick on the front side made up of two ordinary panes 3 mm thick separated by a cork tape. This cover is placed directly on the edges of the internal mirrors which are provided with a rubber seal. This configuration allows the easy opening of the cooker to have access to the absorber.

To reach very high temperatures, it is necessary to increase the radiation absorbed by the absorber. For this, we use a flat mirror reflector arranged on a plywood plate which is fixed on the upper edge of the box. The fixing is ensured by aluminum hinges. These hinges allow the reflector to be oriented when the system is exposed to the sun. Outside of operating moments, the reflector is folded down and the cooker is closed.

During the period of use of the solar cooker, it is oriented so that the direct solar radiation is perpendicular to its opening surface. This technique allows better capture of solar radiation and a longer duration of use daily because the operation of the cooker can be obtained at sunrise (**Figure 1**).

(a) (b)

Figure 1. Box type solar cooker with inclined surface, (a) open reflector cooker and (b) reflector cooker and open glass.

3. Theoretical Studies

3.1. Heat Exchange between the Glass and the Outside Environment ($Q_{p,av1}$).

The heat exchange between the glass and the external environment ($Q_{p,av1}$) is mainly due to the transfer of heat by convection and by radiation.

$$Q_{p,av1} = \left(h_{c,v\text{-}am} + h_{r,v\text{-}sky}\right)\left(T_v - T_{am}\right) \tag{1}$$

where $h_{c,v\text{-}am}$ is the coefficient of exchange by convection between the glass and the ambient,

$h_{r,v\text{-}sky}$ radiation exchange coefficient between the glass and the sky,

T_v is the temperature of the window (K),

and T_{am} : Ambient temperature (K),

$h_{c,v\text{-}am}$ is given by:

$$h_{c,v\text{-}am} = 5.67 + 3.86 V_{Wind} V_{Wind}\left(\text{Wind speed}\right) < 5\ \text{m/s} \tag{2}$$

$$\text{and}\quad h_{r,v\text{-}sky} = \frac{\sigma\varepsilon_v\left(T_v^4 - T_{sky}^4\right)}{T_v - T_{am}} \tag{3}$$

where $\sigma\varepsilon_v$ is the Boltzman constant (m²kg/s⁻²·K⁻¹), ε_v : glass emissivity and T_{sky} the sky temperature is determined by $T_{sky} = 0.0552 T_{am}^{1.5}$;

Equation (1) becomes:

$$Q_{p,av1} = h_{c,v-a}\left(T_v - T_{am}\right) + \sigma\varepsilon_v\left(T_v^4 - T_{sky}^4\right) \tag{4}$$

3.2. Heat Exchange between the Glass and the Absorber ($Q_{p,av2}$)

The heat exchange ($Q_{p,av2}$) between the glass and the absorber is by convection and by radiation.

$$Q_{p,av2} = \left(h_{c,p\text{-}v} + h_{r,p\text{-}v}\right)\left(T_p + T_v\right) \quad (5)$$

$h_{c,p\text{-}v}$: Coefficient of heat transfer by convection between the glass and the absorber and

$h_{r,p\text{-}v}$: coefficient of heat transfer by radiation between the glass and the absorber given by:

$$h_{r,p\text{-}v} = \frac{\sigma\left(T_p + T_v\right)\left(T_p^2 + T_v^2\right)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_v} - 1} \quad (6)$$

where:

T_p: Absorber temperature (K);

T_v: Glass temperature (K);

ε_v :Emissivity of the glass;

ε_p: Emissivity of the absorber;

To determine the convection coefficient $h_{c,p\text{-}v}$, the following correlations are used:

$$N_u = 1 + 1.44\left[1 - \frac{1708\left(\sin 1.8\beta\right)^{1.6}}{R_a}\right]\left[1 - \frac{1708}{R_a \cos\beta}\right] + \left[\left(\frac{R_a \cos\beta}{5830}\right)^{1/3} - 1\right] \text{ [9] } (7)$$

β: angle of incidence of the cooker and

R_a: Rayleight's number

$$R_a = \frac{g\left(T_p - T_v\right)L_c^3}{T_{ma}V_a\alpha_a} \quad (8)$$

L_c: characteristic length (space between the absorber and the glass);

g: intensity of gravity ($m \cdot s^{-2}$);

α_a: thermal diffusivity of air ($m^2 \cdot s^{-1}$);

V_a: the kinematic viscosity of air ($m^2 \cdot s^{-1}$);

T_{ma}: the average temperature of the air between the absorber and the glass, given by:

$$T_{ma} = \left(T_p + T_v\right)/2 \quad (9)$$

$$\text{And } V_a = \mu_a/\rho_a \quad (10)$$

μ_a: dynamic viscosity of air ($kg \cdot m^{-1} \cdot s^{-1}$);

ρ_a: density of air ($kg \cdot m^{-3}$);

α: thermal diffusivity of air:

$$\alpha = \lambda_a/\rho_a Cp_a \quad (11)$$

Cp_a: heat mass of air at constant pressure ($J \cdot kg^{-1} \cdot K^{-1}$);

λ_a: thermal conductivity of air ($W \cdot m^{-1} \cdot K^{-1}$);

$$N_u = h_{c,p\text{-}v} L_c / \lambda_a \tag{12}$$

From which we get the convection coefficient:

$$h_{c,p\text{-}v} = N_u \left(\lambda_a / L_c \right) \tag{13}$$

Duffie and Beckman have given an empirical relationship due to Kelvin for the calculation of the overall exchange coefficient before U_{av}, with an error of less than ±0.3 W/m² [9].

$$U_{av} = \left(\frac{N}{\frac{C}{T_{pm}} \left[\frac{T_{pm} + T_{am}}{N + f} \right]^e} + \frac{1}{h_{c,v\text{-}a}} \right)^{-1} + \frac{\sigma \left(T_{pm} + T_{am} \right) \left(T_{pm}^2 + T_{am}^2 \right)}{\frac{1}{\varepsilon_p + 0.00591 N h_{c,v\text{-}a}} + \frac{2N + f - 1 + 0.133\varepsilon_p}{\varepsilon_v} - N} \tag{14}$$

U_{av} : Loss coefficient of the front panel (W/m²·K),

N: Number of glass

$$f = \left(1 + 0.089 h_{c,v\text{-}a} - 0.1166 \times h_{c,v\text{-}a} \times \varepsilon_p \right) \left(1 + 0.07866 N \right), \tag{15}$$

$$h_{c,v\text{-}a} = 5.67 + 3.86 \times V_{wind} \tag{16}$$

$C = 520\left(1 - 0.000051\beta^2\right)$ for $0^\circ < \beta < 70^\circ$, and for $70^\circ < \beta < 90^\circ$ We take $\beta = 70^\circ$,

$$e = 0.43\left(1 - 100 T_{pm}\right), \tag{17}$$

ε_g : Glass emissivity,

T_{pm} : Average plate temperature (K).

4. Experimental Measurements

4.1. Stagnation Tests

The prototype box-type solar cooker studied is exposed to solar radiation without any charge (empty heating plate). During the test period, the ambient temperature, the temperature of the heating plate also called absorber, the temperature of the indoor air (Tr), as well as the incident solar illumination, are measured.

4.2. Tests with Load

During the various cooking tests, the following parameters are measured: the ambient temperature, the temperature of the hot plate, the temperature inside the kitchen utensil and the incident global solar illumination. The temperatures are measured using thermocouples, that of the heating plate is fixed in the middle of its surface. The overall solar irradiance is measured using an EPPLEY type pyranometer, with a conversion coefficient k equal to 10.41 mV/W/m² and an error in the measured irradiance ±10 W/m². The kitchen utensil used for these tests is an aluminum pan with a lid, painted black. Its total volume is 2.5 liters and its weight is 0.3 kg.

The preliminary cooking tests focused on the cooking of certain foods: eggs and rice. These tests were carried out to gauge the limits of the prototype in terms of maximum temperatures reached and its capacity to cook certain food products with evaluation of the cooking time (**Figure 2**).

5. Results and Discussion

5.1. Operation of the Solar Cooker without Load

The measurements carried out without load are intended to study the operation of the solar cooker.

Initially, measurements were taken in the morning in different places of the cooker before the experiment. The temperatures resulting from these different measurements are lower than room temperature. We deduce that during the night, there are heat losses by infrared emission.

The cooker is then exposed to the sun. The absorber temperature (Tp) increases to 92˚C, while the indoor air temperature (Tr) is around 83˚C after one hour. The system therefore has a low thermal inertia. Despite the variations in the illumination due to the numerous cloudy passages, the stagnation temperature of the indoor air is around, 90˚C and that of the absorber, 101˚C, after two hours. The greenhouse effect is not negligible. The double-glazed glass face increases the greenhouse effect and minimizes the heat losses from the absorber to the outside environment. There is also a slight variation in the temperature of the bottom and the side faces during operation. The cooker therefore has good thermal insulation. The ambient air temperature (Ta) varies between 30 and 32˚C. The different fluctuations in the lighting testify to the numerous cloudy periods. These different observations are perceptible in **Figure 3**.

(a) (b)

Figure 2. (a) Photograph of the solar cooker in use mode, (b) Photograph of the kitchen Utensil.

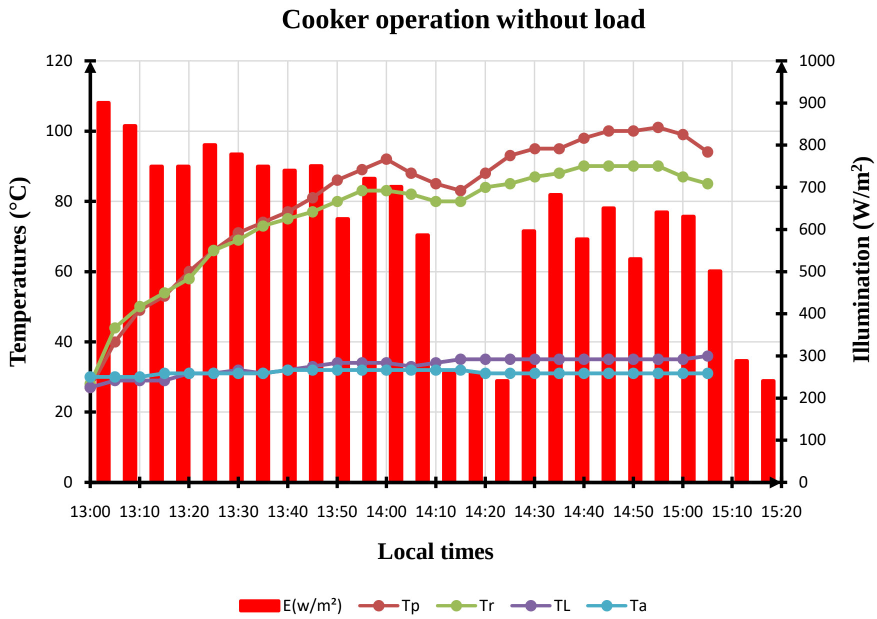

Figure 3. Histogram of the illumination and curves of evolution of the temperatures of the absorber, the indoor air, the ambient air and the side faces as a function of time.

5.2. Egg Cooking Test

The egg cooking test took place on 25/10/2019. We cooked two eggs in a saucepan containing 0.5L of water. The average overall illumination was 609.77 w/m^2. The test started at 10: 25 and ended at 12:55. Intermittent cloudy periods were observed throughout the test. The various measurements taken made it possible to plot the histogram and the curves of **Figure 4**. The histogram shows the variation of the illumination and the curves show the evolution of the temperatures of the indoor air (Tr), of the absorber (Tp), and cooking (Tw) as a function of time. The absorber temperature curve is permanently below that of the indoor and cooking air. The optimum temperature for the absorber is 115˚C and that for cooking is around 100˚C. This temperature is sufficient for cooking by boiling [10] [11]. During this test we see that the histogram of the illumination presents fluctuations which are due to the numerous cloudy passages. The disturbances are partially observed on the temperature curves of the absorber and the indoor air but less on the cooking temperature.

5.3. Rice Cooking Test

The test started at 1:00. and ended at 3:20. The cooker was this time previously heated in the sun. We have taken the readings of temperatures and lighting in the different compartments of the cooker. The histogram of the illumination and the curves of evolution of the different temperatures are represented in **Figure 5** from the quantities noted during the test. The ambient temperature is around 34˚C and the average global illumination is 533.76 w/m^2. As indicated by the results in **Figure 5**, the temperature of the cooking utensil reached 82˚C at 13:35 after 35 min of cooking and 100˚C at 14:30, corresponding to a cooking time of

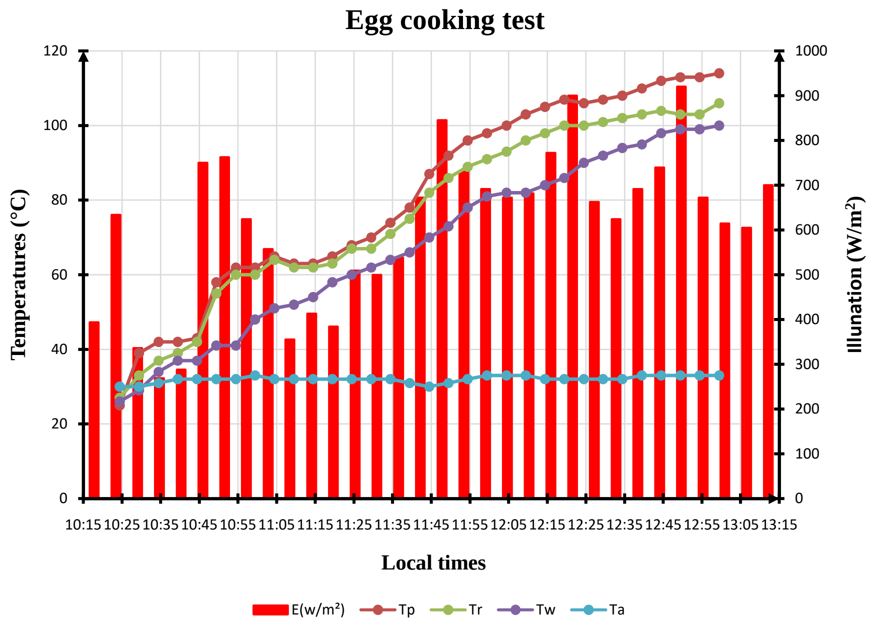

Figure 4. Histogram of the illumination and evolution curves of the temperatures of the absorber, the indoor air and the utensil as a function of time during the cooking of eggs.

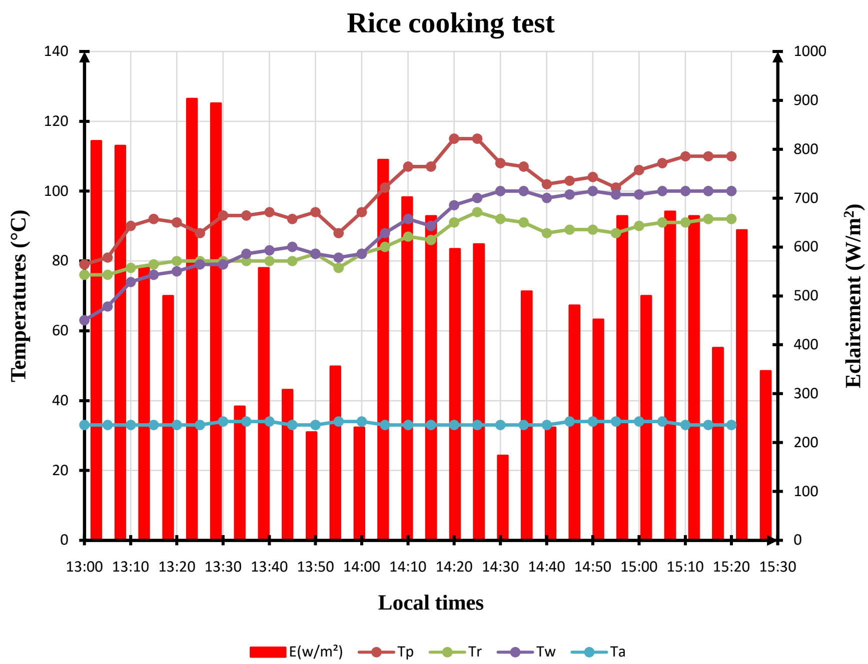

Figure 5. Histogram of the illumination and evolution curves of the temperatures of the absorber, the indoor air and the utensil as a function of time during the cooking of the rice.

1:30. The test continued until 15:20 local time, which corresponds to a total cooking time of 2:20. The absorber temperature reached 115˚C.

The cooking of eggs and rice respects the maximum cooking time given by "Solar cookers international" [12] Figure 6 shows the rice and eggs after cooking.

Figure 6. Photograph of rice and eggs after cooking.

6. Conclusion

This article presents the results of an experimental study of cooking food from a box-type solar cooker carried out in unfavorable climatic conditions. The temperatures of the absorber during the tests are around 115˚C and that of the ustencil 100˚C. The ambient temperature varies between 30˚C and 34˚C and the average global illumination is around 533.76 w/m^2. These various tests have shown that food can be cooked using this prototype solar cooker in the rainy season. The cooking time is acceptable and the taste of the cooked food is very good because the cooking was done under very mild temperatures. The cooking tests are also in the range of international solar cooker. The experimental tests, carried out during the short rainy season show good performance of the solar cooker.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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