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EXPERIMENTAL AND COMPARATIVE STUDY OF TWO SOLAR COOKERS: BOX COOKER AND PARABOLIC COOKER

Coffi Wilfrid Adihou[a,b]*, Grâce Chidikofan[a], Melhyas Kple[c], Maurel Aza-gnandji[c], François Lokossou[d], Aristide Comlan Houngan[e], Malahimi Anjorin[f]

[a]Laboratory of Engineering Sciences and Applied Mathematics (LSIMA) of the National University of Science, Technology, Engineering and Mathematics (Abomey), Benin
[b]Process and Technological Innovation Laboratory (LaPIT) of the National Higher Institute of Industrial Technology (Lokossa), Benin
[c]Rural Engineering Laboratory, National University of Agriculture (Ketou), Benin
[d]Laboratory of Innovative Processes for Sustainable Energy (PIE) (ESMER), Benin
[e]Multidisciplinary Research Laboratory for Technical Education (LARPET), National University of Sciences, Technology, Engineering and Mathematics, Lokossa BP 133, Bénin
[f]Laboratory of Applied Energetics and Mechanics (LEMA) Abomey-Calavi, Benin

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*Corresponding author
adihouwilfrid@unstim.bj

Graphical abstract

Abstract

The aim of this work is to experiment and compare the operation of two solar cookers, namely a parabolic solar cooker and a box solar cooker in order to encourage the population to use solar thermal equipment. For this purpose a parabolic cooker fitted with a mirror as a reflector and a box cooker were created. These two sensors are tested under the same conditions following the international standard procedure for testing solar cookers and reporting performance. Under a solar flux varying between 250 W/m^2 and 1009.78 W/m^2, the maximum water temperature is 108.87°C and 98.02°C at the parabolic cooker and the box cooker, respectively. The parabolic cooker has a standardized cooking power than the box cooker. The specific boiling time is 0.41 h.m^2.Kg^{-1} and 0.54 h.m^2.Kg-1 for the parabolic cooker and the box cooker respectively. The output of the parabolic cooker is higher than the canned one in the morning. The two efficiencies decrease as a function of time and in the evening the efficiency of the parabolic collector becomes lower compared to that of the box cooker. In view of these results, solar cookers can be used in our climate zone to meet certain cooking energy needs.

Keywords: Solar cooker, Efficiency, Temperature, cooking power, boiling time

1.0 INTRODUCTION

Heat is one of the forms of energy fundamentally used by man to satisfy one of his basic needs. This heat is used both in households and in businesses. In households, this heat is used for cooking, heating, drying, etc. To meet this basic need in households, especially that of cooking food, wood biomass is the energy most used in most African countries [1]. Wood biomass represents 90% of all the energy used in cooking food [2] [3] [4]. Fuelwood represents 90% of wood harvested from African forests and a third of the world's energy wood population [5]. In sub–Saharan Africa, wood energy contributes to more than 80% of the total [6] [7] [8]. Which represents a significant quantity of wood for basic energy needs due to the low carbonization yield of between 8% and 20%. [6] [8] [9]. It is then the most important cause of deforestation in Africa and thus constitutes a great threat to the environment with all its consequences on the health of the population. In fact, wood energy represents a significant portion of greenhouse gas emissions. For example, in Benin, Togo, Niger and Ivory Coast, wood energy represents respectively 54.62 %, 72 %, 76,50 % and 50.80% of the total CO2 emitted in 2020 [10-11-12-13]. Furthermore, the use of wood, charcoal or other wood products for cooking in households is one of the main causes of household air pollution in developing countries and in rural communities of developed countries; which also constitutes a source of threat to human health.

According to the latest WHO report [14], this indoor air pollution was responsible for around 3.2 million deaths per year in 2020. It also causes non-communicable diseases, including stroke, ischemic heart disease, chronic obstructive pulmonary disease (COPD) and lung cancer [15].

To reduce these threats to the health of the population and our environment, it is necessary that other sources of thermal energy be identified for domestic thermal needs. This is how the WHO recommends, to reduce indoor air pollution, the use of clean fuels and technologies such as solar energy, electricity, biogas, liquefied petroleum gas (LPG), natural gas, alcohol fuels, and biomass stoves that meet the emissions targets set out in these guidelines. This recommendation is approved by all African countries. This is why the different governments of the different states of Africa are implementing policies of reforestation and energy crops, the use of domestic gas and the popularization of high energy performance stoves. Despite all these efforts, wood energy consumption continues to increase each year. This proves the need to integrate other possibilities to satisfy the thermal energy needs in our homes such as solar cooking technologies which are increasingly targeted. Over the past ten years, solar cooking technologies have been the subject of several scientific researches in Africa and around the world. In 2013, A. Harmim and al experimented with a solar cooker integrated into the wall of a building and realized that the absorber can reach a temperature of 166°C in the hot season in the climatic conditions of Adrar [16]. In 2014, VP Sethi et al studied the performance of a solar collector in a box placed horizontally with a cylindrical container and that of another collector in an inclined box with a parallelepiped container. Experience has proven that the inclined solar cooker is more efficient compared to the box cooker placed horizontally [17]. To increase the solar flux received by the absorber, Gianluca Coccia and al designed and tested a solar cooker with multiple reflectors in 2017. The results obtained with peanut oil as fluid show a temperature above 200°C [18]. Atul A. Sagade et al for their part experimentally determined the concentration ratio of a solar cooker with a single reflector and showed that a solar cooker equipped with a reflector has greater performance than a cooker without a reflector [19]. In 2020, Seth M. Ebersviller and James J. Jetter compared the performances of three types of solar cookers, namely a parabolic solar cooker, a box type cooker and a planar cooker. The results of their experiments reveal that the parabolic solar cooker has a higher firepower compared to the other two but the maximum power measured is still much lower than the firepower of a conventional fuel cooker [20]. These various works have revealed the advantages of solar cooking and heating systems. The aim of this article is to present the possibility of making efficient parabolic solar cookers with locally available and inexpensive materials. Specifically, firstly, it presents the parabolic solar cooker made with the materials used and secondly it compares the performances of the parabolic cooker made with those of the conventional boxed solar cooker.

2.0 METHODOLOGY

2.1 The Cookers Tested

The cookers tested are the parabolic cooker and the box cooker. The box cooker served as a reference to assess the performance of the parabolic cooker.

The parabolic solar cooker consists of the reflector, the pot support, the main support and the manual orientation system for tracking the sun.

Reflector consists of a satellite receiver dish covered by small mirrors cut and placed on the interior surface of the dish. These 3mm thick mirrors are cut into a 5 cm from side and have their shiny sides facing the sun (Figure 1).

Figure 1 Reflector made

The dish used has an opening diameter D=0.8m and a height H=0.08m (Figure 2).

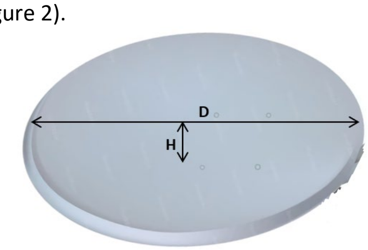

Figure 2 Technical characteristics of the parabola used

The focal length f is related to the height and diameter by the equation

$$H = \frac{D^2}{16.f} \quad [1]$$

So f is determined by

$$f = \frac{D^2}{16.H} \quad [2]$$

Cooking pot or absorber is made of aluminum with a transparent glass cover. Aluminum is the material generally used for cooking pots in West Africa and particularly in Benin.

Pot support is made of 3 mm thick galvanized steel welded to the support of the entire device.

The parabolic concentrator requires a sun tracking system to capture the maximum solar flux. For this system, we adopted a very simple manual tracking mechanism based on 3 cylinders (Figure 3a) and a rotating axis (Figure 3b) to turn the solar oven to the position of the sun at any time

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Figure 3 simple manual tracking mechanism (a) Jack (left). (b) rotating axis (right)

The parabolic cooker is compared to a box cooker also made with locally available materials. The casing of this box cooker is double-walled. The exterior wall is made of 1 cm thick wood and the interior wall is made of plywood. The two walls are separated by expanded polystyrene 1.5 cm thick. The transparent cover is made of transparent double glazing. The interior is covered with aluminum foil to encourage the reflection of solar rays towards the pot which represents the absorber. As in the case of the parabolic cooker, the pot is made of aluminum painted matte black.

The two cookers tested are shown in Figures 4 and 5 below.

Figure 4 Cooker in box

Figure 5 Parabolic cooker

2.2 The Different Steps Of Design

The construction of the two cookers is based on the use of locally available materials. The main steps followed for the construction of the two cookers are as follows:

2.2.1 Parabolic Cooker

1st step: construction of the sensor
A mirror with a thickness of 3mm and a surface area of 1m2 was cut into small square mirrors with a side of 5cm. These small mirrors were placed over the entire surface of a 0.8 m diameter parabola using strong glue.

2nd step: determination of the focal length

It is determined by equation [2]. It allows us to know the position of the pot.

3rd step: construction of the support
This step consists of creating a support assembly consisting of a sensor support and that of the pot to facilitate the rotational movement of the sensor and those of rotation and translation of the pot support.

4th step: assembly of the entire cooker
At this stage, the various components were assembled and the various temperature sensors were placed.

2.2.2 Cooker In A Box

1st step: making the box
The box was made of double walls (wood and plywood) separated by polystyrene. The interior is covered in aluminum foil

2nd step: making the glazing support
The transparent surface is double glazed. This support is made of wood and allows a spacing of 3 cm between the two panes.

3rd step: installing the panes
The panes are placed on the glass support to ensure sealing.

4th step: assembling the box and the glazing
The box and the glazing system are assembled. Seals are used to ensure sealing. The glazing system constitutes the door of

the cooker. At this stage, the various temperature sensors are installed.

After these different stages of making the two cookers, the two pots are painted in matte black.

2.3 Experimental Study

The experimental tests were carried out on July 14 and July 15, 2020 at the higher school of renewable energy professions (ESMER), located in Abomey-Calavi, South Benin (6°24'28.2°20'24.9''E) between 10:00 a.m. and 3:00 p.m. Tests on the cookers were conducted using the American Society of Agricultural Engineers Standard ASAE S-580.1.

Tests on the cookers were conducted using the American Society of Agricultural Engineers Standard ASAE S-580.1. The quantity of water in each pot is defined according to the FUNK procedure [21]. For the box cooker whose intercepted surface area is 0.2 m^2, the quantity of water in the pot is 1.4 kg. For the parabolic cooker, the quantity of water is 3.5 kg because the opening surface is 0.5 m^2.

During the experimental period, ambient temperature (Ta), global solar irradiance and diffuse solar irradiance were measured using the “PV sensor Kit” from the “Unit for Solar Hydrogen Production” (Figure 6) consisting of a pyranometer and a Temperature sensor (Figure 7).

Figure 6 Heliocentris acquisition unit

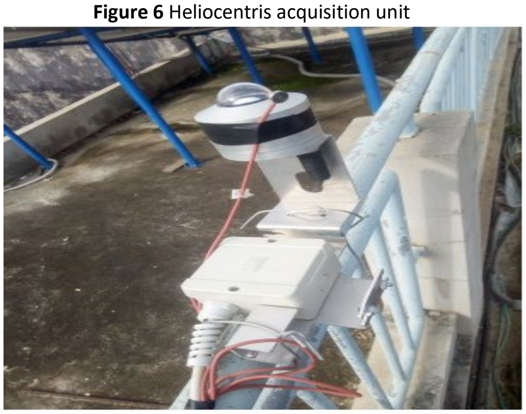


Figure 7 Agilent 34970A acquisition unit

Wind speed was measured by “Tektronix TD8901 digital anemometer” (Figure 8). Type K thermocouples are used to measure temperatures of pots, water in pots. All of the thermocouples are connected to the “Agilent 34970A” acquisition unit (Figure 9). During the tests, two multimeters are used to check pot temperatures from time to time.

Figure 8 The anemometer used

Figure 9 Agilent 34970A acquisition unit

The different values of the different measured parameters are processed with Excel software. These different values make it possible to trace the curves of the different parameters presented in the results and analyzes section. These different parameters are the temperature of the pot, the temperature of the water in the pot, the ambient temperature, the solar illumination, the cooking power, the adjusted cooking power and the energy efficiency of the cooker. The various tests were carried out following the “the international standard procedure for testing solar cookers and reporting performance” [21]. For this, the measurements were carried out between 10 a.m. and 3 p.m. local time (11 a.m. and 4 p.m. GMT) on July 14 and 15, 2020.

The performance of solar systems is influenced by the angle of incidence. To increase the heat flow received by the cookers, they are manually oriented every 10 minutes according to the position of the sun.

2.3.1 Specific Boiling Time

It is a theoretical parameter which evaluates, for a solar cooker, the boiling time for a surface corresponding to one kg of fluid. It is defined based on the boiling time, the surface of the sensor and the mass of the fluid brought to the boiling point. Its expression is that of formula (3) [22].

$$t_{sp} = \frac{\Delta t_e . A_c}{m} \quad [3]$$

Δt_e is the boiling time of water

The factor that corresponds to the area proportional to 1 kg of fluid can be called the nominal area of the sensor $\frac{A_c}{m}$

Using the specific boiling time, we can determine another parameter defined by Khalifa et al [22] as the characteristic boiling time t_c according to formula (4).

$$t_c = t_{sp}\frac{\overline{I}}{I_n} \quad [4]$$

$\overline{I}$ is the average irradiation of the period when the water passes from its initial temperature to the boiling temperature and I_n is the solar irradiation standardized to 700 W/m² [21]

This characteristic boiling time can be useful to compare solar cookers.

2.3.2 Cooking Power

The thermal performance of solar cookers is evaluated according to the International Standard procedure developed by Funk [21]. According to this Standard, the cooking power P of the solar cooker is calculated when a specific mass of water is maintained inside the cooking utensil. Solar cookers are put into service under certain conditions described in the Funk Standard. And as the water will heat up during operation, its average temperature is monitored and recorded during a particular time interval of 10 min (Δt = 600 s). The average power delivered during this interval is expressed by the following formula:

$$P = \frac{(M_w.C_{Pw}).\Delta T_w}{\Delta t} \quad [5]$$

Where M_w is the mass of water, CP_w is the specific heat capacity of water (CP_w= 4190 J.kg^{-1}K^{-1}).

ΔT_w is the water temperature difference after 10 minutes ($\Delta t = 10\,\text{min}$)

2.3.3 Standardized Cooking Power

Funk [21] also introduced the term: adjusted or standardized cooking power P_{adj}, in order to facilitate comparison between different solar cookers under different lighting intensities. The adjusted cooking power is given by equation (6), where $\overline{I}_b$ is the average solar irradiation of each 10 min.

$$P_{adj} = P\frac{I_n}{\overline{I}_b} \quad [6]$$

Taking into account equation (5), the adjusted cooking power becomes:

$$P_{adj} = \frac{(M_w.C_{Pw}).\Delta T_w}{\Delta t}.\frac{I_n}{\overline{I}_b} \quad [7]$$

To evaluate the performance of solar cookers, the evolution of the adjusted cooking power is determined according to the difference in water and ambient temperatures. By introducing the ambient temperature into equation 7 we have:

$$P_{adj} = \frac{(M_w.C_{Pw})(T_{wf} - T_a + T_a - T_{wi})}{\Delta t}.\frac{I_n}{\overline{I}_b} \quad [8]$$

$$P_{adj} = \frac{(M_w.C_{Pw})(T_{wf} - T_a)}{\Delta t}.\frac{I_n}{\overline{I}_b} + \frac{(M_w.C_{Pw})(T_a - T_{wi})}{\Delta t}.\frac{I_n}{\overline{I}_b} \quad [9]$$

T_{wi}, T_{wf}, and T_a are respectively the initial water temperature, the final water temperature and the ambient temperature.

According to the tests of this Standard (Protocol), the wind speed should be low and the water temperature inside the cooking pots should be between 40°C and 90°C for solar cookers in boxes and between 40°C and 95°C for parabolic solar cookers. Ambient temperature and solar illuminance should be between 20 to 35°C and 450 to 1100 W/m², respectively.

2.3.4 Energy Efficiency Of The Cooker

The first law of thermodynamics gives energy efficiency (η) as the ratio of output energy to input energy. The energy efficiency of box and parabolic solar cookers is calculated using equation (10) below :

$$\eta = \frac{(M_w C_{Pw}).(T_{wf} - T_{wi})}{\overline{I}_b.\Delta t.A_c} \quad [10]$$

3.0 RESULTS AND DISCUSSION

The amount of energy produced by solar cookers depends on the amount of heat they are exposed to and the surrounding conditions. For the two test days (July 14 and 15, 2022), the ambient temperature and irradiation during the day are presented in Figure 10 and Figure 11 below.

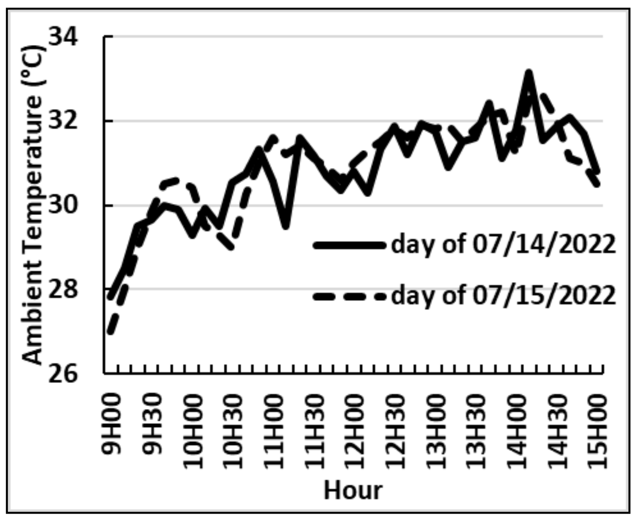


Figure 10 Ambient temperature evolution

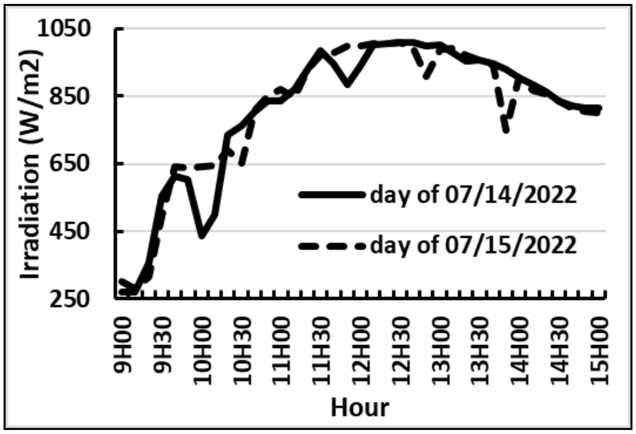


Figure 11 Irradiation evolution

For the two days of testing, the ambient temperature presents values between 27.82°C and 33.14°C for the day of 07/14/2022 and then between 27°C and 32.6°C for the day of 07/15/2022. The temperature values recorded for these two days do not show enough differences. The highest difference is 0.7°C and is observed at 11:10 a.m. The solar radiations of the two test days also present similar values. The radiation values are between 269.53 W/m^2 and 1010.44 W/m^2 on 07/14/2022 and then between 281.1 W/m^2 and 1010.6 W/m^2 on 07/15/2022. Taking into account the cloud covers which do not produce at the same time during two days, some small differences were noted between the two radiation curves. The largest difference is observed at 10:00 a.m. and presents a momentary difference of 203.81 W/m^2.

The values of ambient temperatures and solar radiation from the two test days present practically the same values. The results obtained during the tests also present practically identical values. This is why the values of the different parameters of the two cookers presented in this work come from the results of the single day of 07/14/2022.

Figure 12 shows the pot and hot water temperatures for the parabolic cooker and the box cooker. The different curves generally reveal two zones. A zone of strong growth at the beginning and a zone of gradual decline at the end. The high growth zone takes 12.5 hours. The temperatures presented by the parabolic cooker are all higher than those presented by the box cooker. In the high growth zone, pot and water temperatures vary respectively from 53.96°C to 135.78°C and from 37°C to 108.83°C for the parabolic cooker and respectively from 54.07°C to 105 .47°C and from 36.41°C to 98.02°C for the box cooker. The maximum values of the different temperatures are obtained at the end of the high growth zone. The maximum temperature reached by the water at the parabolic cooker is 106.58°C and that of the box cooker is 95.01°C.

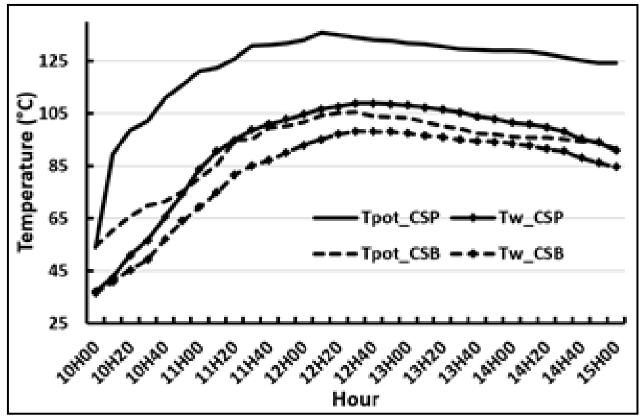
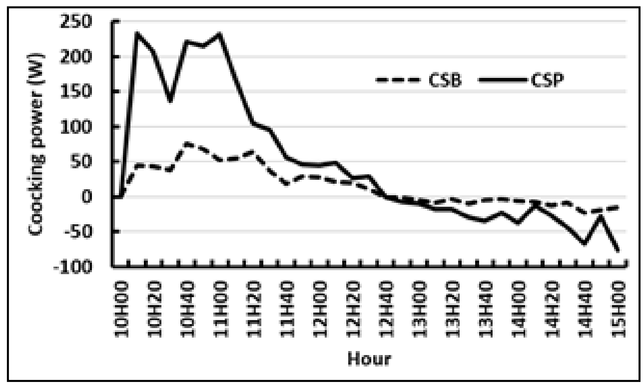


Figure 12 Evolution of pot and water temperatures

The appearance presented by the different temperatures is justified by the evolution of the solar radiation curve presented in Figure 10. From 10 a.m. to 12:30 p.m. the water gains thermal energy and its internal energy increases while After 12 hours 30 minutes, the heat flow is no longer sufficient to increase the internal energy of the water. This phenomenon is clearly clarified by the evolution of the cooking power presented in Figure 13



. **Figure 13** Cooking power as a function of time

Figure 13 shows that the cooking power is positive in the zone of strong growth in solar flux between 10 a.m. and 12:30 p.m. and it is negative in the zone of gradual decrease in solar flux going from 12:30 p.m. to 3 p.m. Consequently, a very beneficial use of the solar cooker is made in the zone of growth in solar flux and not very beneficial in the zone of decrease in solar flux. We can simply remember that the use of solar cookers is recommended in the growth zone with solar flow. It is also evident from the curves in Figure 12 that the cooking power for the parabolic cooker is higher than that of the box cooker. But the box cooker is little influenced by the intermittency of the solar rays caused by the presence of temporary clouds in the sky while the parabolic cooker is strongly influenced by it.

The adjusted cooking powers of the two cookers are presented in Figure 14 and Figure 15.

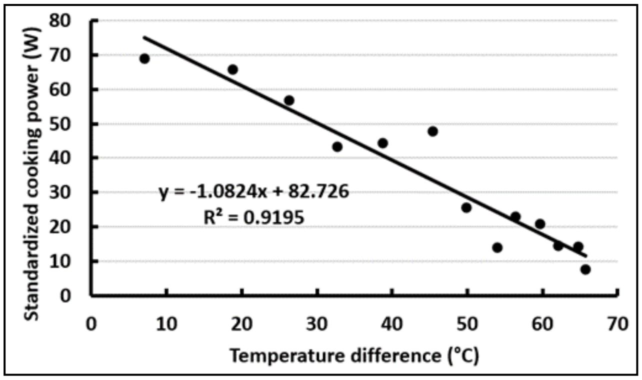


Figure 14 Cooking power adjusted for Box Cooker

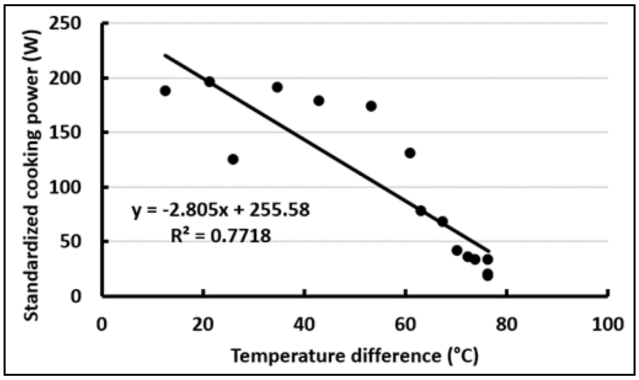


Figure 15 Cooking power adjusted for parabolic cooker

The adjusted cooking powers are a function of the temperature difference ΔT between the hot water temperature and the ambient temperature. The regression lines of the adjusted cooking powers of the box and parabolic solar cookers are respectively P_CSB=82.73-1.08ΔT and P_CSP=255.58-2.80ΔT. These equations show that the slope of the regression line of the parabolic cooker (2.80 W/°C) is higher than that of the box cooker (1.08 W/°C). These slope values reveal that heat losses are higher in the parabolic cooker than in the box cooker; which justifies the large difference between the temperature of the pot and that of the water observed at the level of the parabolic cooker (Figure 12). On the other hand, the initial values of these regression line equations prove that, under the same environmental conditions, the adjusted cooking power is higher for the parabolic cooker.

For a temperature difference ΔT = 50°C, the adjusted cooking power is respectively equal to 28.73 W and 115.58 W. this means that the cooker is more powerful than the box cooker.

The thermal efficiencies of the two solar cookers presented in Figure 16.

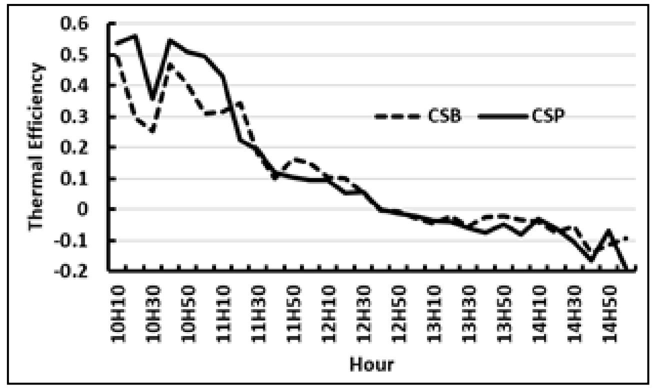


Figure 16 Thermal efficiency of the solar cookers tested

Thermal efficiencies are higher at the beginning and decrease over time. We then see that the thermal efficiency decreases when the water temperature increases. The hotter the water, the lower the efficiency. Between 10 hours and 12:30 hours, the yields are positive and the parabolic cooker has overall higher yields than the box cooker. For the parabolic cooker, the efficiency varies between 5.27% and 56.08% and between 9.9% and 49.28% for the box cooker. After 12 hours 30 minutes, the thermal efficiencies are negative and thus indicate an area that is not useful for continuing heating. Based on the criteria of thermal efficiency and cooking power, we can conclude that the parabolic cooker is more efficient than the box cooker. This deduction is confirmed by the characteristic boiling time of 0.41 for the parabolic cooker and 0.54 for the box cooker. The parabolic cooker is faster than the box cooker.

4.0 CONCLUSION

The adoption of solar cookers for domestic cooking is not successful enough in our countries which benefit from plenty of sunshine throughout the year. This study provides an overview of the operation of solar cookers by comparing two types of solar cookers, namely a parabolic cooker and a box cooker. According to the tests carried out, the water is brought to the boil in 1 hour 40 minutes and in 2 hours 30 minutes respectively for the parabolic cooker and for the box cooker. The test results revealed that the parabolic cooker performs better compared to the box cooker. We can also notice through these tests that the water in the pot for the parabolic cooker reached the boiling temperature (100°C) at 11:40 a.m. The temperature of this water remained above 100°C until 2:20 p.m., a duration of approximately 2 hours 40 minutes before dropping to 99.79°C. This shows that this cooker can be used for cooking dishes with short and medium cooking times. When using a box cooker, the maximum water temperature in the pot is 98.2°C. it can then be used for dishes that require a short cooking time. The use of these cookers not only reduces expenses related to the purchase of fuels but also slows down deforestation because the fuels most used in the region are wood and charcoal.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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