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Performance Tests and Thermal Efficiency Evaluation of a Modified Solar Box Cooker in a North-Central City of Nigeria

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Abstract

This study reports the performance and thermal efficiency evaluation of a modified solar box cooker at a project site in Makurdi, Benue State, Nigeria. The hourly variations of five different temperature measurements as well as standard water heating tests and controlled food cooking tests carried out during the periods of November and December, 2013 are also presented. The results of this investigation showed that, a maximum temperature of 90oC was attained for the water heating tests. The controlled cooking tests results also revealed that, the device took 1hour 30 minutes and 2 hours. 20 minutes to cook egg and rice respectively. The efficiency of the device was calculated to be 42.13%. This value of thermal efficiency is lower than that of the original work. However, if the same initial temperature conditions of the working fluid of about 65^0C and 62^0C were considered as in the case of the original work, an efficiency of 53.22% would have been obtained which is higher than that of the original work. This high value of efficiency is predicted to be due to the black paint applied to the entire inner surface of the solar box cooker. It is therefore recommended that this device should be used as a pre-cooking and alternative to firewood.

Keywords: solar box cooker, thermal efficiency, water heating tests, food cooking tests, firewood.

1.0 Introduction

A significant proportion of the Nigerian population as in many other developing countries in Africa, Asia and Latin America depend on fossil fuels, biomass and firewood for cooking and domestic water heating. Recent studies revealed that in Nigeria, domestic cooking and heating account for more than
70% of the energy need of most households [1].

The main cooking fuels in the rural areas in Nigeria are wood fuel and agricultural wastes. In the urban and sub-urban cities, the main cooking fuels are kerosene, liquefied petroleum gas (LPG) otherwise called cooking gas, and electricity. There is no gain saying the fact that, conventional sources of energy for domestic cooking like kerosene, liquefied petroleum gas and electricity are characterised by irregular availability, increasing costs and some are mostly not environmentally friendly. For example, the use of wood fuel, biomass, kerosene and liquefied petroleum gas for cooking introduces carbon dioxide (CO2) and other harmful substances (or green house gases) in the household environments which contribute to global warming and climate change. The persistent use of wood fuel for cooking in addition leads to soil erosion, deforestation and desertification.

Solar energy is one of the main alternative renewable sources of energy crucial to our search for domestic fuel replacements. This is because, it is the source of almost all renewable and non-renewable sources of energy. Also, it is the cleanest, free from environmental hazards, readily available and inexhaustible. However, like the development of all other energy sources, the breakthrough of solar energy into the technological world will involve a lot of planning, organization, generation and diffusion of information as well as the provision of infrastructure or devices to harness it for efficient and various effective uses.

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Nigeria is blessed with abundant amount of sunshine which has been estimated to be 3,000 hours of annual sunshine [1]. A solar cooker is powered by energy from the sun and thus can be used as an alternative cooking device. There are several case histories detailing the construction of various types of solar cookers in Nigeria, however, a lot still need to be done in this area of study so as to improve on the already existing designs. Bello et al [1] constructed and tested a solar box cooker at a Guinea Savannah station in Ilorin. A maximum temperature of 88oC was attained by the cooker and an average efficiency of 47.56% was obtained from the cooker. Taura and Musa [2] carried out design, construction and testing of a single-glazed solar cooker for two weather situations in Kano. A maximum temperature of 100oC and an efficiency of 31.57% were obtained from the cooker. In the same vein, Rikoto and Garba[3] in their work investigated the effect of solar cooking using box- type solar cooker with finned and unfinned cooking pots. Tests carried out revealed that cooking time can be reduced by using a finned cooking pot.
In this work, a modified solar box cooker similar to the one constructed in [1] has been constructed. The authors of this work have investigated the effect of painting the entire inner surface of the box black on the thermal efficiency of the cooker.

2.0 Mathematical Modelling of Solar Radiation of the Study Site

The study site of this research is Makurdi town. Makurdi is the capital of Benue State which is located in the North-Central part of Nigeria. The coordinates of Makurdi are: Latitude 7o41'N, Longitude 8o37'E and altitude 106.4m above sea level [4]. The town is located along the coast of the river Benue [5]. Makurdi has a monthly temperature between 27.38oC and 28.00^{0}C and may go up to a maximum of 30-34oC. The area receives between 900-1000mm of rain annually [6]. The dry season starts in late October and usually ends by March, while the rainy season lasts from April to early October [6].
In this work, the average global solar radiation value for the months of November and December, 2013 of 459Wm^{-2} [4] has been used for the estimation of the thermal efficiency of the solar box cooker. The monthly average extraterrestrial radiation the relation [1].

$$\overline{H_0} = \frac{24}{\pi} I_s \left[1 + 0.0334 C_O \left(\frac{2\pi}{365} - 3\right)\right] Z \qquad (1)$$

$$Z = (C \quad ¤ C t \quad , \delta - \omega, S \quad ¤ S \quad)$$

$$\delta = 23.45 S \quad \left[360 \left(\frac{284 + J}{365}\right)\right] \qquad (2)$$

Where:

I_s = solar constant taken as 1367Wm^{-2}

J = The Julian day with $J = 1$ on 1st January and 365 on 31st December

¤ = Latitude of the site of investigation which is Makurdi

$\delta =$ The declination angle of the sun. Usually 15th day of each month is the day on which the solar declination angle, δ is calculated [7] and

ω_s = the sunset hour angle which is given in [8]:

$$\omega_s = C \quad ^{-1}(-t \quad ¤ \; t \quad) \qquad (3)$$

The monthly average of the maximum sunshine hours per day at the location is given in [8]:

$$S_m \quad = \frac{2}{15} C \quad ^{-1}(-t \quad ¤ \; t \quad) \qquad (4)$$

The monthly average clearness index $\overline{K_T}$ is given in [9]:

$$\overline{K_T} = \frac{\overline{H}}{\overline{H_0}} \qquad (5)$$

Where $\overline{H}$ is the monthly average global solar radiation on a horizontal surface.

3.0 Collector Efficiency

The efficiency of a solar collector is a measure of the collector performance and it is the ratio of the useful heat gain per unit area of the collector to the solar energy flux on the collector. That is [2]:

$$¦_c = \frac{Q_U}{H_T A_C} \qquad (6)$$

The efficiency of the cooker can therefore be calculated using the relation[1]:

$$¦_c = \frac{\left(m_p C_p + m_w C_w\right)(\overline{T_w} - \overline{T_u})}{A_c H_T t} \qquad (7)$$

Where:

$m_p = m$ o the c u (p)

$m_w = m$ o w in the c u

$C_p = s$ he c o he p (i.e. al)

$C_w = sp$ he ca o w

$\overline{T_w} = a$ w te

$\overline{T_u} = a$ a te

$A_c = a$ a o the s cc

$H_r = a$ g s ra (in W^{-2})a

$t = d$ ti p o i

4.0 Methodology

5.0 Construction Procedure

As earlier mentioned, this work is a modification of the solar box cooker constructed in [1]. In the original design, only the absorber plate below the box was painted black, the inner walls of the box were left reflecting. However, in this work, the entire inner surface of the box is painted black. A trapezoidal shaped inner box of dimension 30cm x 30cm x 20cm bounded by an outer box measuring 80cm x 60cm x 30cm was constructed for this study. The two boxes were made from mahogany planks. Aluminium sheet of thickness 0.5mm was glued to the inner box. The aluminium was painted black to absorb and retain the heat needed for cooking. For the insulation of the cooker, sawdust was used to fill the space between the inner and the outer box. For the glazing, two transparent glass panes of thickness 4.0mm each were fitted on top of the cooker with a space of 10mm between them so as to create green house effect which is the basis of operation of the solar device. A big plane mirror of thickness 4.0mm measuring 60cm x 40cm was used as the reflector. The reflector consists of a wooden frame which is sized to form a cover for the box when not in use. The box was inclined at an angle of 23^0 to ensure that maximum irradiation falls on it. Makurdi the study site is located on Latitude $7^0$41'N(7.68oN) and according to Eze et al[10] and Oji et al[11], solar collectors in the Northern hemisphere are best mounted or placed facing southwards and inclined at an angle given by the summation of the latitude of the area and 15^0. Thus, for Makurdi, the site of this work, the optimum angle of inclination for the solar collector is:

Latitude $+15^0$ $= 7.68^0 + 15^0$

$= 22.68^0 \approx 23^0$

Figures 1a-c and 2 show the construction details and outer view of the solar box cooker respectively.

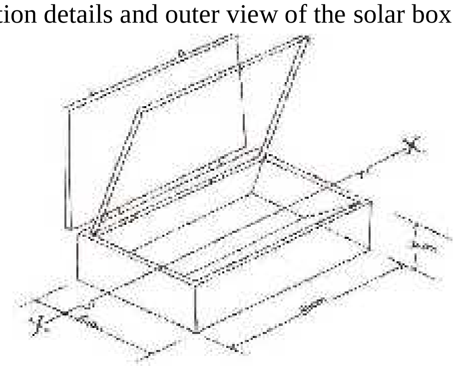

Figure 1a: Isometric View of the Solar Box Cooker.

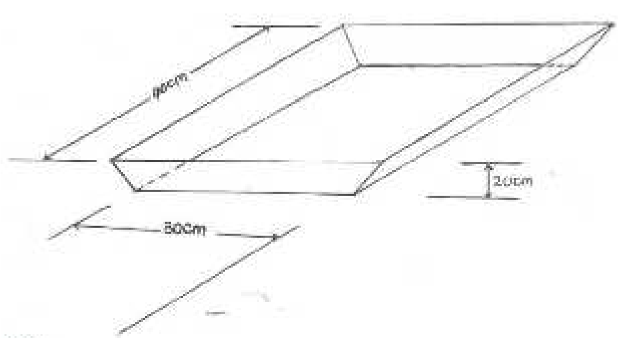

Figure 1b: Inner Absorber Tray.

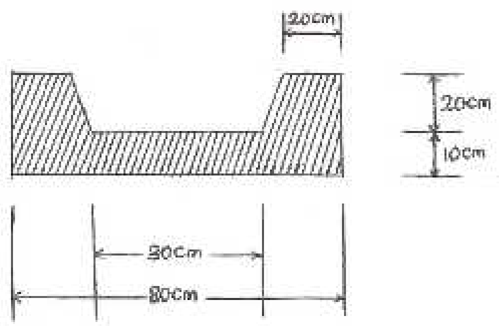

Figure 1c: Section X-X.

Figure 2: Outer View of the Solar Box Cooker.

6.0 Experimental Procedure

The solar cooker was positioned in an open space at Unique Secondary School, Makurdi, Benue State. The thermal system was placed facing southwards where there were no trees or shade of any sort so as to maximize the solar radiation falling on it. The cooking device was allowed to heat for about 10 minutes before inserting the load. The device was exposed to direct sunlight to allow incident solar energy fall on it while the reflector was adjusted manually at regular intervals of 30 minutes to ensure that the reflected rays covered the entire glazing surface.

The performance tests conducted were: (i) water heating tests which involve temperature measurements connected with the photo-thermal system for the period it takes to heat the water as well as (ii) controlled cooking tests. During the experimentation on the water heating tests, the following temperature readings were observed and recorded:

- Ambient temperature, Ta
- Insulator temperature, Ti
- Working fluid (water) temperature, Tw
- Absorber plate temperature, Tp and
- Cooking chamber temperature, Tc.

For the water heating tests, a black painted aluminium pot of mass 0.27kg containing 500cm3 (0.5kg) of water was placed on the absorber plate of the solar box cooker and placed outdoor for observations. Similarly, for the controlled cooking tests, the food to be cooked plus 750cm3 of water contained inside the black painted pot were placed in the box and the unit was placed outside for necessary measurements to be observed and recorded. The various temperature and time measurements were measured on hourly basis from
11:00 hours to 17:00 hours using mercury-in-glass thermometers and a stop watch throughout the period of study. The results are presented in section 4.0 of this work.

7.0 Results and Discussion

The results of the hourly variations of temperature measurements observed in the months of November and December, 2013 using the modified solar box cooker are presented in Tables 1 and 2 :

Table 1: Results of temperature measurements observed with time using the modified solar box cooker on 13th November, 2013.

Time (Hour)	Ta (^{0}C)	Ti (^{0}C)	Tw (^{0}C)	Tp (^{0}C)	Tc (^{0}C)
11:00	31.0	32.0	30.0	41.0	40.0
12:00	35.0	34.0	62.0	73.0	70.0
13:00	36.0	38.0	76.5	80.0	80.0
14:00	37.0	44.0	86.0	84.0	87.0
15:00	37.0	46.0	90.0	86.0	91.0
16:00	36.0	46.0	87.0	84.5	88.0
17:00	34.0	46.0	84.0	81.0	85.0

Table 2: Results of temperature measurements observed with time using the modified solar box cooker on 11th December, 2013.

Time (Hour)	Ta (^{0}C)	Ti (^{0}C)	Tw (^{0}C)	Tp (^{0}C)	Tc (^{0}C)
11:00	31.0	32.0	31.0	41.0	41.0
12:00	35.0	36.0	49.0	61.0	60.0
13:00	35.0	40.0	65.0	71.0	76.0
14:00	36.0	44.0	78.5	80.0	84.0
15:00	36.0	46.0	84.5	83.0	87.5
16:00	34.5	46.0	82.0	80.0	83.0
17:00	32.0	44.0	78.0	76.5	79.0

8.0 Efficiency of the Solar Cooker

The efficiency of the solar cooker is calculated using equation (7) i.e.

$$\eta_c = \frac{\left(m_p C_p + m_w C_w\right)(\overline{T_w} - \overline{T_a})}{A_c H_T t}$$

Where:

Mass of pot, $m_p = 0.27k$

Mass of water in the pot, $m_w = 0.5k$

Specific heat capacity of pot, $C_p = 920 JK^{-1}K^{-1}$

Specific heat capacity of water, $C_w = 4200 JK^{-1}K^{-1}$

Average water temperature, $\overline{T_w} = 70.25^0C$

Average ambient temperature, $\overline{T_a} = 34.68^0C$

Aperture area of solar collector, $A_c = 0.12m^2$

Average global solar radiation, $H_T = 459Wm^{-2}$

Daily time period of investigation, $t = 3600s$

$$\therefore \eta_c = \frac{(0.27 \times 920 + 0.5 \times 4200)(70.25 - 34.68)}{0.12 \times 459 \times 3600} = 42.13\%$$

Considering that the same initial temperature conditions of the working fluid of about 65oC (in November) and 62oC (in December) were used as in the original work, the thermal efficiency would have been:

Mass of pot, $m_p = 0.27k$

Mass of water in the pot, $m_w = 0.5k$
Specific heat capacity of pot, $C_p = 920JK^{-1}K^{-1}$
Specific heat capacity of water, $C_w = 4200JK^{-1}K^{-1}$
Average water temperature, $\overline{T_w} = 79.41^0C$
Average ambient temperature, $\overline{T_a} = 34.68^0C$
Aperture area of solar collector, $A_c = 0.12m^2$
Average global solar radiation, $H_r = 459Wm^{-2}$
Daily time period of investigation, $t = 3600s$

$$\therefore \eta_c = \frac{(0.27 \times 920 + 0.5 \times 4200)(70.25 - 34.68)}{0.12 \times 459 \times 3600} = 42.13\%$$

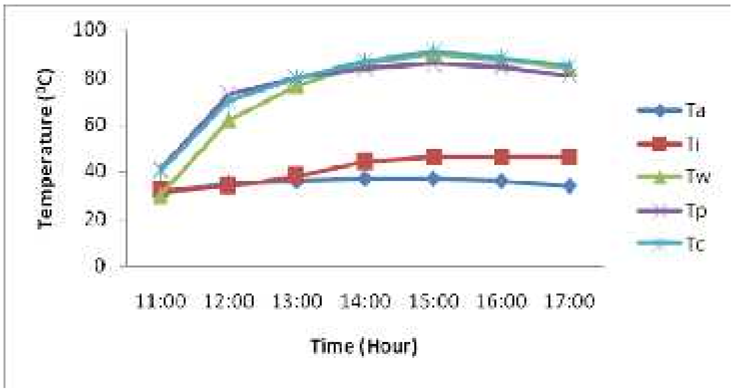

Figure 3: Graph of Temperature Versus Time using the modified solar box cooker on 13th November, 2013.

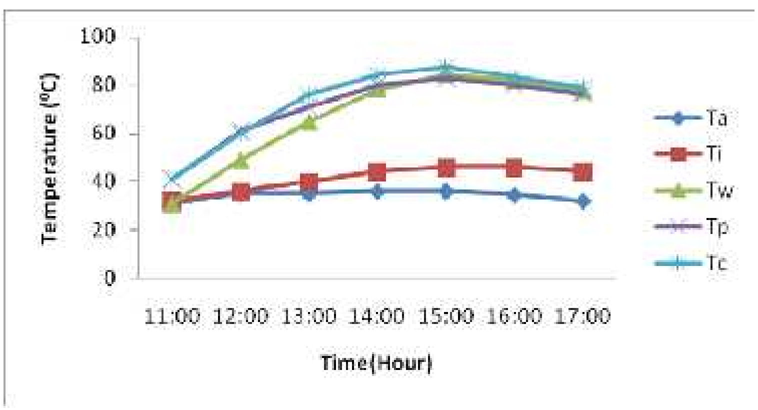

Figure 4: Graph of Temperature Versus Time using the modified solar box cooker on 11th December, 2013.

Figures 3 and 4 show the hourly variations of the ambient temperature (Ta), insulator temperature (Ti), working fluid (water) temperature (Tw), absorber plate temperature (Tp) and cooking chamber temperature (Tc) observed in the months of November and December, 2013. As shown in Figure 3, a maximum temperature of the working fluid of about 90oC was attained around 15:00 hours (3pm) on this day of investigation in November (13/11/2013). Also, Figure 4 indicates that, a maximum temperature of the working fluid of about 84.5oC was attained around 15:00 hours (3pm) in the month of December (11/12/2013).

In general, it can be observed that, at the early hours of the day, the temperatures increased rapidly. For the second hour, the rate slows down. The temperature of the cooker begins to drop gradually after the peak temperature. Also, it is evident that, the differences between the absorber plate temperature, Tp and cooking chamber temperature, Tc is not quite significant. This is possibly a reflection of the good emittance and selective surface properties of the absorber plate. Bello et al[1] reported that the required minimum food cooking temperature is 82oC. The results of the performance tests carried out in this

work suggest that, this temperature was attainable during the periods of investigation in November and December. This therefore indicates that the modified solar box cooker is quite good for optimum use during these periods in the area of study.
After the experimentation on the water heating tests, controlled cooking tests were carried out to examine the effectiveness of the cooker. The device was used to cook egg and rice (0.180kg). The tests were conducted from 11:00 hours to 15:00 hours and it took 1hour 30 minutes (11:00am -12:30pm) to cook egg and 2 hours 20 minutes (12:40 - 3:00pm) to cook rice which is comparable to the result obtained in [1].
The efficiency of the modified solar box cooker has been calculated based on the results of the water heating tests conducted. The efficiency was calculated to be 42.13%.

9.0 Conclusion

The following conclusions have been drawn from this study:

i. The performance evaluation of the modified solar box cooker showed that the cooker can heat water to a maximum of 90^0C which is higher than the value of 88^0C obtained in [1].

ii. The time taken by the solar device to cook egg and rice (0.180kg) was respectively found to be 1hour 30 minutes and 2 hours 20 minutes while that of Bello et al[1] took 1 hour 30 minutes and 2 hours 30 minutes to cook the same quantity of egg and rice respectively. The device took a long time to cook the egg due to weak intensity of solar radiation in the early hours of the day.

iii. The thermal efficiency of the solar box cooker was found to be 42.13% which is lower than the value of 47.56% obtained in [1] for a similar cooker investigated in the Guinea Savannah Region of Nigeria. However, if the same initial temperature conditions of the working fluid of 65oC (in November) and 62^0C (in December) were used as in the original work, a thermal efficiency of 52.22% would have been obtained. This therefore implies that painting the entire inner surface of the solar box cooker black will give a better performance than painting only the absorber plate below the box black.

10.0 References

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