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Performance Evaluation of a Solar Box Cooker at Mautech, Yola, Nigeria

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Abstract:
A constructed solar box cooker with aperture area of 0.408 m^2 has been evaluated under the climatic conditions of MAUTECH, Yola using the stagnation and cooking test techniques. With $F_1 \cong 0.12$ and $F_2 \cong 0.19$ the solar box cooker was found suitable for cooking at the location. It can offer 27 J of heat under average solar radiation intensities ≥ 750 Wm^{-2} to the cooking content per second. Though it takes longer time to cook, it may be used as an outside kitchen cooking alternative for a patient house wife.

1. Introduction

One of the necessities of man worldwide is domestic cooking. In facts, studies have shown that domestic cooking and heating account for more than 70% of the energy needs for most households [1, 2, 3]. How the cooking is done has led man to the discovery of varieties of cooking fuel around him. Problem with cooking arises when the fuel is either scarce or expensive. Most of the conventional energy sources popularly known to man for cooking includes: wood, animal dung, agricultural residues, liquid petroleum gas (LPG), kerosene and coal. Out of these varieties, firewood has been found dominant in most households in Nigerian. In recent times, this conventional method of cooking has been found to be hazardous to health and environment. The exhaust produced from burning of these fuels increases the greenhouse gasses and pollutes the environment thereby causing global warming and acid rain [4].
To be freed from the dangers associated with the use of these fuels, there is need to search for environmentally friendly alternatives. The fact that Nigeria is blessed with abundant amount of sunshine estimated to be 3000 hours annually [5] makes it a better alternative for cooking. Solar energy is a free gift of nature; it does not pollute and is always available for use. As a result, several designs have been made in the area of solar energy utilization for cooking.

In this work, a solar box cooker has been constructed and evaluated at Moddibo Adama University of Technology Yola (MAUTECH). Yola is a semi-arid climate zone of Nigeria, located at latitude $9^0.20'$N and $12^0.30'$E. Solar cooker cooks by converting the sun rays into heat, and then transferring it onto the pot. Solar box cookers are fire and smoke free, they are simple, cheap and easy to construct; it has high acceptance angle and uses both direct and diffuse radiation, has comparative performance under cloudy conditions, and it is safe to use.

2. Materials and Methods

2.1. Description of Constructed Solar Box Cooker

The solar box cooker used in this work is made of plywood with glass aperture area *A* of 0.68 by 0.6 (0.408 m^2) fixed on the covered lid. It is lined from the inside walls with crinkled Aluminum sheets and at the bottom with a black absorber plate made from steel. The Aluminum linings at the walls are to reduce heat loss by reflecting back radiation unto the black cooking utensil surface. The box cooker is designed to accommodate only one cooking utensil at a time. Between the metal plates and the outer plywood are packs of thermal insulation materials (rice husk) to reduce heat loss through conduction. Based on the nature of the ground level at the site of the experiment (Modibbo Adama University of Technology, Yola, Nigeria) and the requirements for optimum collection of solar radiation through the aperture surface, an inclination angle of 24^o with respect to the ground surface was found suitable for the non-tracking box cooker.

2.2. Experimental Procedure

Three days were used for the experiment; first day for the stagnation test and the remaining days for the cooking test. The solar box cooker was positioned without load in the sun from10:30 am and allowed to freely absorb solar radiation. Readings of absorber plate temperatures alongside the corresponding values of the solar irradiance at intervals of 15 minutes were recorded till steady state was reached at which time the plate temperature was found to stagnate at 131^oC.

A cooking utensil of mass 0.30kg made from aluminum containing 1 kg of water was placed inside the solar box cooker and then positioned in the sun from 10:30 am for the cooking test. Readings of the water temperatures, ambient temperatures and solar irradiance were recorded starting from 10:45 am to about 13:15 pm. These procedures were repeated for the following day in order to determine the average performance of the box cooker.

2.3. Theory

When a solar oven is placed in the sun, the internal temperature rises to a nearly constant value after certain time interval at which the box cooker is said to be in thermal equilibrium; the power delivered to the box cooker at such equilibrium point is equal to the power loss from the box. The first figure of merit F_1 that determines how a solar box cooker could thermally perform under this condition is defined as the ratio of the optical efficiency $F'\eta_o$ to the overall heat loss coefficient $F'U_L$[6]:

$$F_1 = \frac{F'\eta_o}{F'U_L} = \frac{T_p - T_a}{H} \tag{1}$$

where H and T_a are respectively the insolation on the box aperture and ambient temperature at plate stagnation temperature T_p. The second figure of merit F_2 is determined from cooking test by specifying the temperature limits T_{w1} and T_{w2} on the sensible heating curve for a given quantity of water heated over certain time interval τ and then calculated from [6]:

$$F_2 = \frac{F_1(MC)_w}{A\tau} ln\left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1}-\bar{T}_a}{\bar{H}}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2}-\bar{T}_a}{\bar{H}}\right)}\right] = F'\eta_o\left[\frac{(MC)_w}{(MC)' + (MC)_w}\right] \tag{2}$$

The sensible time required to boil the water τ_{boil} from ambient temperature is given by [6]:

$$\tau_{boil} = -\frac{F_1\,(MC)_w}{F_2 A\tau} ln\left[1 - \frac{1}{F_1}(100 - \bar{T}_a)\right] \tag{3}$$

The standardized cooking power P_s of the solar box cooker at each plate temperature interval $(T_{wb} - T_{wa})$between the first and second measurements corrected to a standard irradiance of 700 Wm^{-2} is given as [7]:

$$P_s = \frac{M_w C_w (T_{wb} - T_{wa}) \times 700}{\tau \bar{I}} \tag{4}$$

The overall heat loss coefficient U_L for the solar box cooker is determined from the plot of the calculated values of the standardized cooking power P_s against difference between their corresponding water and ambient temperatures for each interval as:

$$U_L = \frac{\text{slope}, m}{\text{aperture area of box cooker}} = \frac{m}{0.408} \tag{5}$$

This assumes that only loss from glass cover is significant as sides and bottom are well insulated.

The value of the standardized cooking power at the temperature difference of 50^oC, called the adjusted cooking power P_a is the single measure of the performance of the solar box cooker in Watts. The 50^oC temperature requirement is such that a balance between the startup cooking and stagnation temperature is established [7].

3. Results And Discussion

The stagnation temperature of the solar box is determined from the plot of the plate temperatures against local time of the day (Figure 1). It could be seen that at a temperature of about 131^oC, the plate temperature is stagnated indicating that equilibrium has been established. The ambient temperature at the stagnation point was found to be about 37^oC under solar irradiance of 795 Wm^{-2}.

Knowing T_p and H, the first figure of merit F_1 for is solar box cooker is calculated from equation (1) and this has a value of 0.1182 which ends it a grade A solar box cooker for having an approximate value of F_1= 0.12 [6].

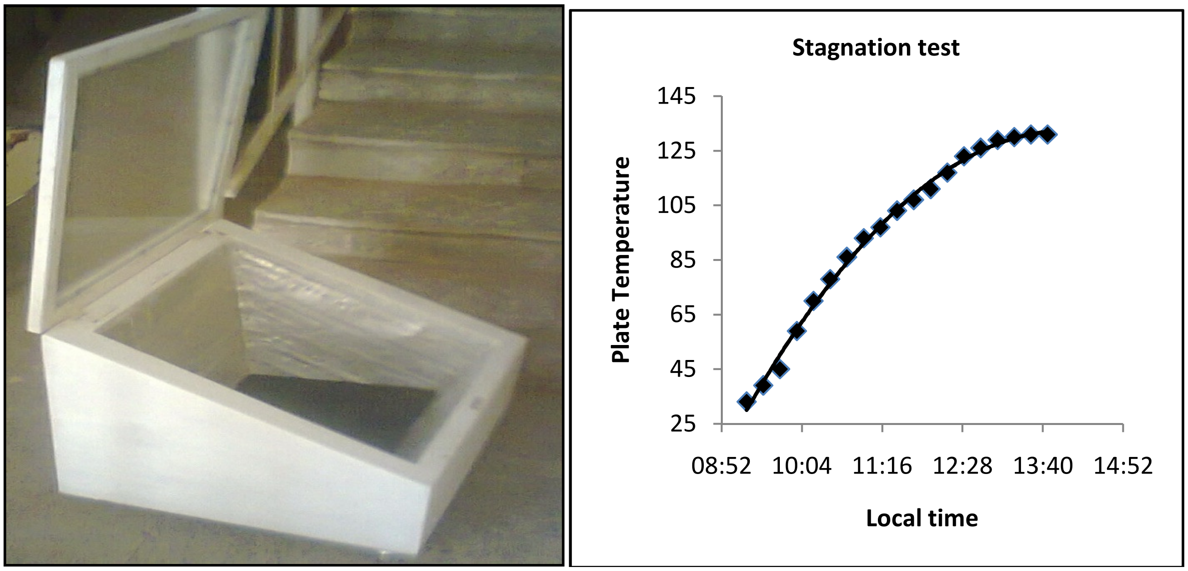

Figure 1: Constructed solar box cooker and stagnation test plot

Figure 2 shows the cooking test plots for day 1 and 2 known as the sensible heating curves. Two reference temperatures T_{w1}=65°C and T_{w2} =95°C were selected on the curves in order to evaluate the second figure of merit F_2.

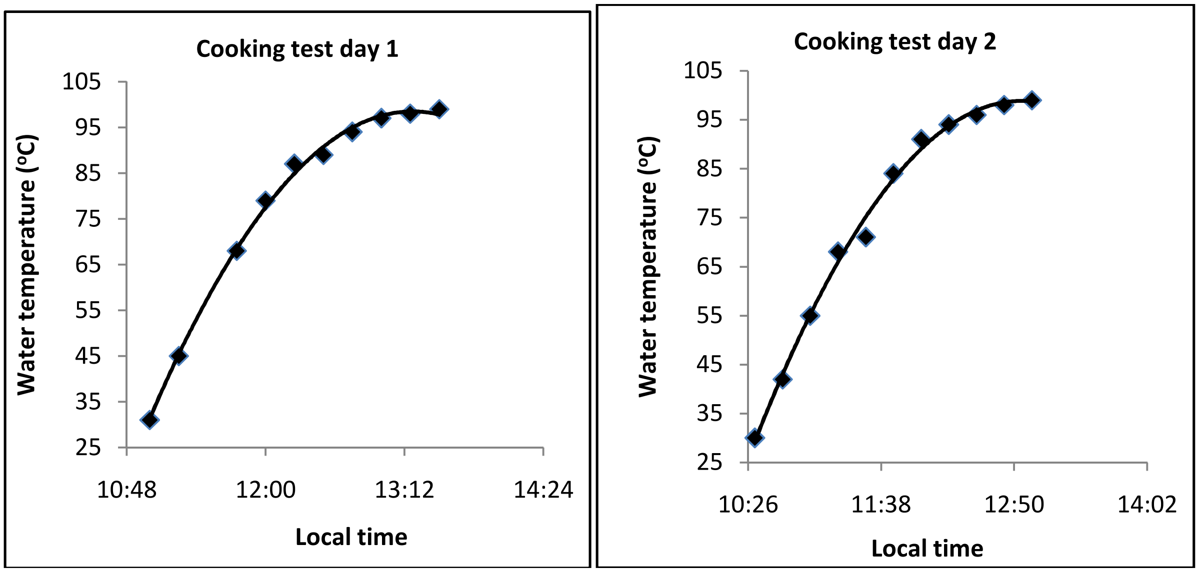

Figure 2: Cooking test plots for day 1 and 2

From the graphs, the time interval required for the water temperature to change from 65°C to 95°C and the average insolation $\overline{H}$ within the time interval τ were measured and presented in Table 1. Also in Table 1 are the calculated values of F_2using equation (2) and the total time τ_{boil} using equation (3) required to boil the water from ambient temperature.

Experiment	T_{w1}	T_{w2}	$\overline{T}_a$	τ	$\overline{H}$	F_2	τ_{boil}	m	U_L	P_a	η_o (%)
Day 1	65	95	36.5	72	757	0.191	131.45	-1.050	2.574	24	30.4
Day 2	65	95	38.5	68	776	0.188	119.95	-1.134	2.779	29	32.8
Average	65	95	37.5	70	767	0.190	125.70	-1.092	2.677	27	31.6

Table 1: Parameters of the solar box cooker

Figure 3 gives the plots of the standardized cooking powers against the temperature difference between water and ambient over the cooking period. Using the linear equations shown on the graphs, the values of P_a and U_L using equations (4 and 5) respectively were presented in Table 1 alongside their corresponding optical efficiency. The low values of the optical efficiency show that the incident solar radiation was poorly collected due to the fact the solar box cooker wasn't a tracking collector hence deficient as the sun changes position. Also, it may be partly due to the steam condensation on the inside surface which reduces the transmittivity of the glazing material.

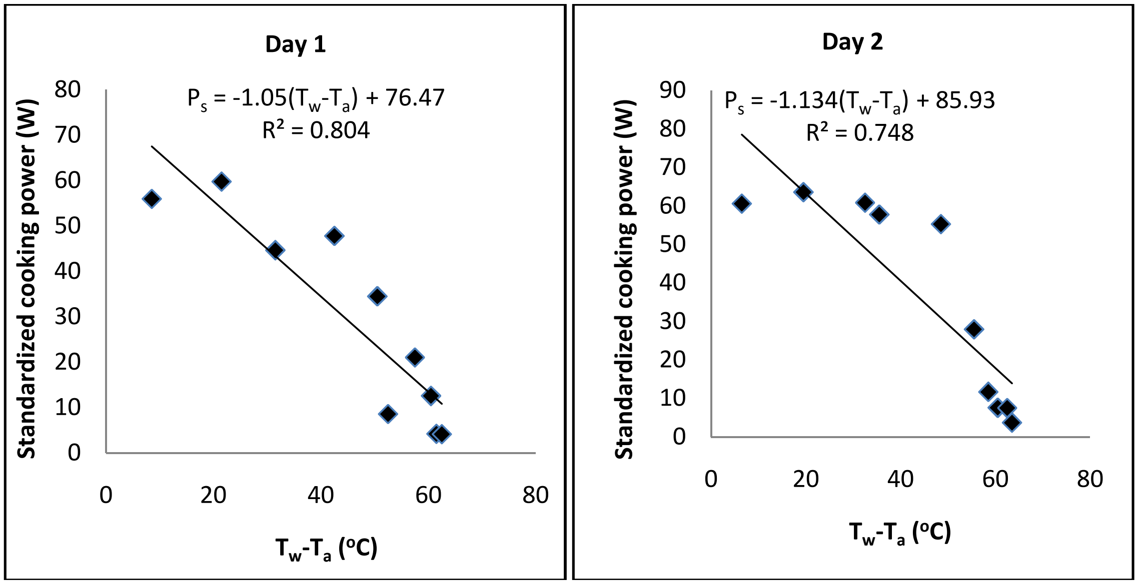

Figure 3: Plots of standardized cooking power against (T_w-T_a) for day 1 and 2

It could be seen from the table that the solar box cooker has an average adjusted cooking power of approximately 27 W. This means 27 J of heat can be added to 1 kg of water in the cooking utensil every second. Therefore, to bring the water to boil, the cooker had delivered about 203.63kJ of heat to the water within the 127.6 minutes. This explains why cooking with solar radiation usually takes a longer time.

4. Conclusion

The parameters of the solar box cooker have shown that it could be patiently used for cooking. With $F_1 \cong 0.12$, it can be considered a grade A cooker that can offer 27 J of heat every second under solar radiation intensities of, at least greater than 750 Wm^{-2}. It is therefore recommended as a kitchen companion.

5. References

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