



DEVELOPMENT OF A SOLAR BOX FOR COOKING AND WATER HEATING.

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ABSTRACT:

Solar cooking is the utilisation of direct insolation harnessed from the sun as energy source in cooking and water heating. In this study, a device for solar collection and direct utilisation for cooking and water heating was developed. The device consisted of two boxes a smaller box 600 mm × 600 mm × 460 mm insulated with coconut coir of thermal conductivity 0.295 Wm^{-1} placed within a larger box 700 mm × 700 mm × 500 mm. The direct solar insolation (I_s), stagnation temperature of the device (T_s), ambient temperature (T_a) and the wind velocity (V) were measured in accordance with ASHRAE standards. The regression procedure of Mini Tab (v.16) was used to relate the cooker temperature (T_c) with I_s , T_s , T_a , and V . The presence of the heat storage unit made it possible to cook beyond 15:00 hours up until 18:00 hours local time while the hot water from the dispensing unit attained temperature of about 65°C for most days of testing at about $13:00 \pm 0:40$ hours and gradually dropped to about $50^\circ\text{C} \pm 5^\circ\text{C}$ by 19:00 hours local time. The First Figure of Merit (F_1) and Second Figure of Merit (F_2) were calculated from the data obtained while the cooking power were calculated in line with ASAE report on testing and reporting of solar cooker performance. The direct solar insolation (762.04 W/m^2), stagnation temperature (130°C), ambient temperature (31.56°C), and wind velocity of 2.6 m/s were used in calculating F_1 and F_2 as 0.1324 and 0.2687 respectively. The cooking power were normalized to 708.92 W in accordance ASAE. The regression model obtained to predict T_c as a function of I_s , T_s , T_a , and V had a coefficient of determination (R_2) of 91.45%. The presence of the rock pebbles and hot water in the device helped to stabilize the cooker temperature consequently increasing the available energy on the heat absorber plate.

Keywords: *Solar Cooking, Coconut coir, Insolation, Hot water, Rock peddles*

INTRODUCTION

The continuous increase in the level of greenhouse gas emissions and the climb rise in fuel prices are the main driving forces behind efforts to more effectively utilize various sources of renewable energy. In many parts of the world, direct solar radiation is considered to be one of the most prospective alternative sources of energy (Sharma *et al.*, 2009). Solar energy commonly considered as a gift of nature is in abundant supply compared with other naturally existing forms of energy such as fossil fuel, coal, oil and natural gas which are fast depleting due to increased global dependence on energy (Ohijeagbon *et al.*, 2006). Water is found on earth in all three forms and . It covers about two-thirds of the surface of earth. However, availability of potable water has remained elusive to human beings in the developing world. It has been established Worldwide, globally that unsafe water is a constitutes a major health problem and is being the root cause of many diseases, especially in developing countries. An estimated 1 billion people do not have access to safe water (Eze *et al.*, 2010). Therefore, the development and the use of solar cookers with a water heating facility will greatly reduce the use of the conventional cooking fuels in the rural and in some selected urban centres, reduce emission of harmful gases to the environment and also provide hot water for domestic use. This research was conceptualised to focused on the development and evaluation evaluate of a solar collection device for direct utilisation in cooking and water heating activities.

MATERIALS AND METHODS

The following materials were used for the fabrication,

- i. Plywood for the box,
- ii. Mild steel for the water system,
- iii. Glass was used as lid,
- iv. Mirror as reflectors,
- v. Coconut fibre was used to lag the box,
- vi. Cooking pot which is a modified Pressure cooker,
- vii. Rock pebbles was used as heat storage material since Rocks store about a third as much heat as water for equal volumes (Stout, 1990) and
- viii. Copper pipe was used to convey water from the external tank to the inner storage tank.

Design Concept

The solar cooker operates on two principles, the greenhouse effect of trapping heat within an enclosed space and the intensification of solar radiation on an absorber plate.

Design Analysis and Calculations

If $MC_p \Delta T$ is the energy required to raise the temperature of the water from T_i to T_f (where $\Delta T = T_f - T_i$) and $I_{av} \eta A_s$ is the amount of solar energy available to boil the water, then the solar radiation collection area (i.e. cooker surface area is obtained as,)

$$A_s = \frac{(MC_p \Delta T)}{(I_{av} \eta)} \dots\dots\dots 1$$

The cooker wall insulation thickness is estimated from Fourier’s law of conduction as,

$$x = \frac{(KA_L \Delta T_p)}{Q_L} \dots\dots\dots 2$$

Where,

A_L is the heat loss area (bottom + side walls).

ΔT_p is the temperature difference between the absorber plate and ambient temperature.

Table 1: Parameters and Assumptions used in the Design.

Parameters for Box Design	
Mass of water to be boiled, M	=1.5kg
Initial water temperature, T_i	=30°C
Desired final temperature of water, T	=100°C
Specific heat capacity of water, C_p	=4200Jkg ⁻¹ K ⁻¹
Thermal conductivity of coconut coir, K	=0.295Wm ⁻¹ 0C ⁻¹
Desired maximum heat loss rate through the cooker walls, Q_L	=7% of I_{av}
Time desired for boiling of water, t	=1 hour
Anticipated average total insolation (during the time t), I_{av}	=700Wm ⁻²
Assumed overall solar cooker efficiency, η	=0.35
Ambient air temperature, T_a	=30°C
Anticipated absorber plate maximum temperature, T_p	=125°C
Solar cooker surface area dimensions (Calculated), A_s	
Thickness of wall insulation (calculated), x	

The energy balance equation for the absorber plate is obtained by equating the total heat gained by the absorber plate to the total heat lost by the heat absorber plate of the solar collector. Therefore,

$$Q_T = Q_e + Q_L \dots\dots\dots 3$$

Q_T = Energy Output

Q_e = Energy Input

Q_L = Energy Lost

The total energy (Q_e) entering the box through the double-glazed cover assuming favourable weather conditions since about 12% of the rays coming from the sun is reflected by each cover as stated by Aremu, (2004)

Description of hot water dispensing system and heat storage unit.

The constant availability of hot water not only helps in the fast cooking of food but also serves as a source of heat storage. The water storage chamber located beneath the absorber plate was made of mild steel with thin vertical mild steel plates which served as fins within the chamber. Water in the storage chamber is heated by the radiant energy trapped by the absorber plate through conduction by the rock pebbles of relatively small diameter beneath the absorber plate and around the water storage unit. The fins were incorporated so as to increase the surface area within the tank and thus reduce the time it would require to heat the water. Copper pipes were also used to connect the vertical fins within the water chamber. The choice of copper for the tube was informed by its excellent heat conducting properties. It is very malleable, ductile and resistant to corrosion. Both the rock pebbles and the water chamber which were painted black to increase absorbance, retention of absorbed heat and subsequent radiation. An external water tank was added to the design with a regulating valve to feed the storage unit with water regularly.

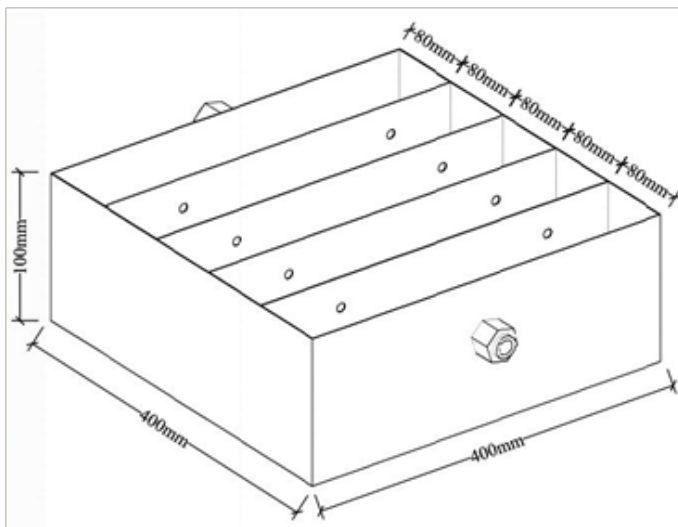


Figure 1: An orthographic view of the internal water storage unit, showing the fins.

Design Of The Box Cooker

A box was constructed using plywood for the body of the cooker, mild steel painted black served as absorber plate and igneous rocks also painted black served as under lay for storage of heat received by the absorber plate. The dimension of the cooker surface area was calculated and other assumption based on certain criteria such as the size of the pot to be used. The cooker was made up of two separate boxes, rhombus in shape with the side walls inclined as an angle to capture maximum solar radiation. The design

parameters and assumptions used in this design are shown in Table 1

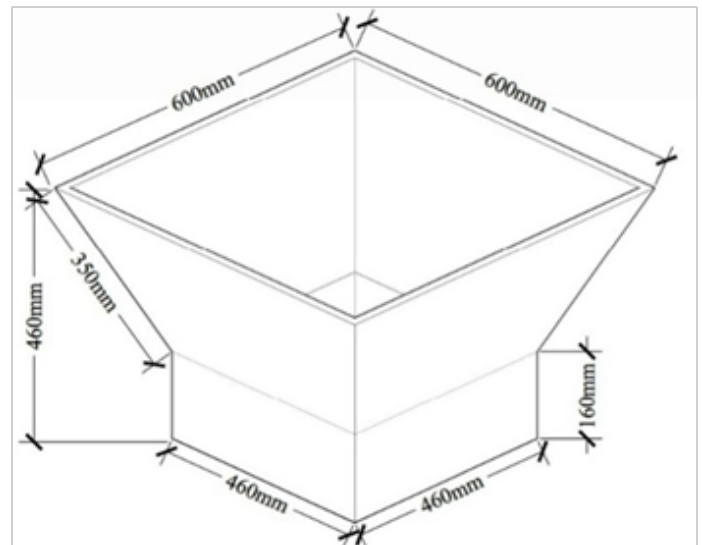


Figure 2: The inner box of the solar cooker

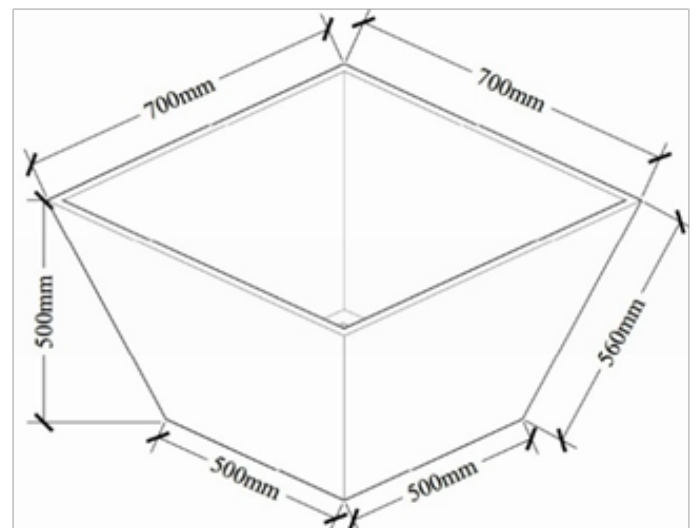


Figure 3: The outer box of the solar cooker

Coconut coir was used as insulator because of its low thermal conductivity and availability was used as lagging material between the two boxes.

A double-glazed lid was also fitted to the box in order to simulate the greenhouse effect which reduces the loss of heat energy by convection and radiation from the absorber plate. For this propose a 4 mm thick glass was used in order to reduced breakage. The glasses were held together by wood and were spaced at 40 mm from each other. Mirrors were also incorporated into the design so as to reflect rays thereby reducing the frequency of alignment of the device to track azimuth angle. The internal walls of the cooker were also covered with reflective materials.

The absorber plate was coated black both front and back with char and it was made up of mild steel of dimension 430 mm × 430 mm and had a thickness of 0.8 mm.

Design of pot

The pressure cooker used for performance evaluation was initially designed to release pressure in form of steam as soon as the pressure inside the pot reaches 80 kPa. The valve was however adjusted so as to pervert steam from being released at 80 kPa to 120 kPa by increasing the weight of the valve from 80 gto 120 g. The pot which is spherical in nature has a diameter of 0.225 m, a height of 0.135 m, a volume of 0.0053m³ and it occupies 22.54 % total surface area of the absorber plate thereby leaving enough room for the plate to absorb the heat energy.

Performance Tests

1. No load tests

This was conducted to evaluate the first Figure of Merit (F₁) of solar cooker which is defined as the ratio of optical efficiency, (η₀)and overall heat loss coefficient, (U_L). A quasi- steady state is achieved when the stagnation temperature is attained. The energy balance horizontally placed empty solar cooker at stagnation is given by equation 4.

$$\eta_0 I_H = U_L (T_c - T_a) \dots\dots\dots 4$$

The First Figure of merit “F₁” defined by equation 5 was used according to American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) standard ASHRAE 93 in regards to testing to determine the thermal performance of solar collectors

$$F_1 = \frac{\eta_0}{U_L} = \frac{(T_c - T_a)}{I_H} \dots\dots\dots 5$$

2. Load Test

The load test was done by the determination of the second figure of merit, F₂ given by Equation 6 according to ASAE, 2003

$$F_2 = F_1 \frac{(MC)_w}{A_c} \ln \left(\frac{1 - \frac{U_L (T_{w2} - T_a)}{\eta_0 I_H}}{1 - \frac{U_L (T_{w1} - T_a)}{\eta_0 I_H}} \right) \dots\dots\dots 6$$

Where

- F₁ is the Figure of Merit of solar cooker,
- η₀ is the optical efficiency,
- U_L is the overall heat loss coefficient.

3. Cooking Power Test

The energy required for cooking at specified interval was calculated according to ASAE standard (2003) and is given by Equation 7 and the Normalized cooking power was obtained from Equation 8. According to ASAE (2003)

$$P_i = (T_2 - T_1) MC / 600 \dots\dots\dots 7$$

where:

- P_i = cooking power (W)
- T₂ = final water temperature
- T₁ = initial water temperature
- M = water mass (kg)
- C = heat capacity (4186 J)/(kg•K)

$$P_s = P_i \left(\frac{7000}{I} \right) \dots\dots\dots 8$$

where:

- I = interval average insolation(W/m²)
- P_i = cooking power (W)
- P_s = standardized cooking power (W), ASAE (2003)

RESULTS AND DISCUSSION

The developed solar cooker is shown in Plate 1 as labelled. Dreveals that during the test, the peak values for direct solar insolation (762.04W/m²), stagnation temperature (130°C), ambient temperature (31.56°C), and wind velocity of 2.6m/s were obtained which were used in calculating F₁ and F₂. The average values were 0.1324± 0.0014 and 0.2687 for F₁ and F₂ respectively. The Normalized cooking power was obtained as 708.92W in accordance ASAE, 2003.



Plate 1: Developed Cooker assembly
A is the insolation reflector
B is the assembled cooking device.

Data obtained during the no load test, showed that between 11 hours and 16 hours local time when insolation was appreciable, the absorber plate temperature was mostly above 100°C, and a maximum temperature of 130°C was recorded at 12:40 local time. It was also observed that the cooker temperature increased with the raise in insolation and ambient temperature, reduced gradually with raise in wind velocity as shown in Figure 4 and Figure 5.

above 80°C from about 10:00 hours to about 17:00 hour and remained above 50°C till late in the evening.

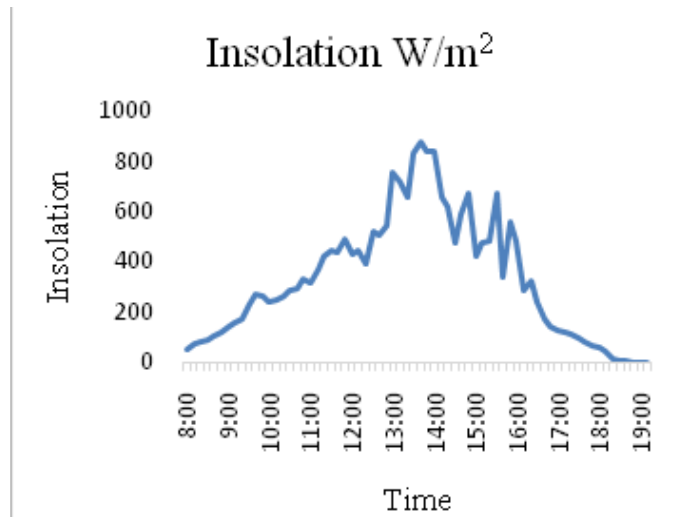


Figure 4: Insolation variation under no-load conditions

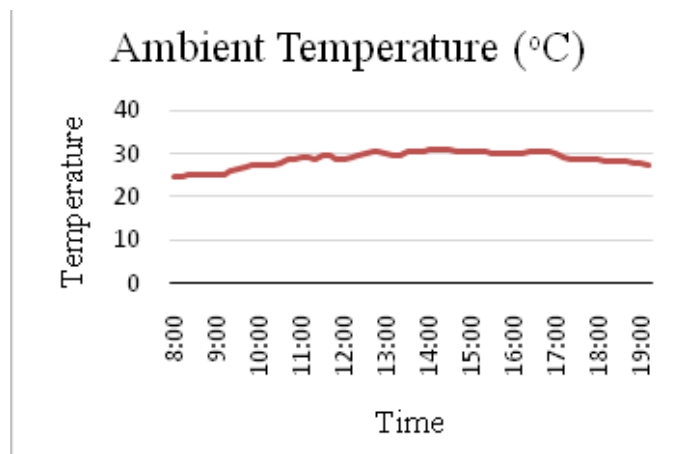


Figure 5: Temperature variation outside the device under no-load

A typical wind velocity obtained during the test is depicted in Figure 6, the wind velocity did not exceed 2.5 m/s for more than ten minutes, according to the American Society of Agricultural Engineers (2003), in any of the test days, the data obtained should be discarded if wind speed exceeds 2.5 m/s for more than ten minutes. The data obtained as shown in Figure 6, depicts the wind velocity obtained during the test and it can be seen that it was below the speculated limit of 2.5 m/s. The cooker temperature as shown in Figure 7 shows that the cooker temperature was

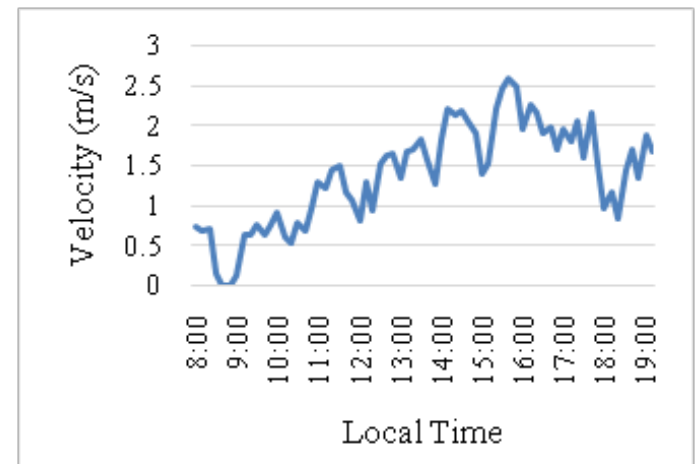


Figure 6: Wind velocity variation outside the device

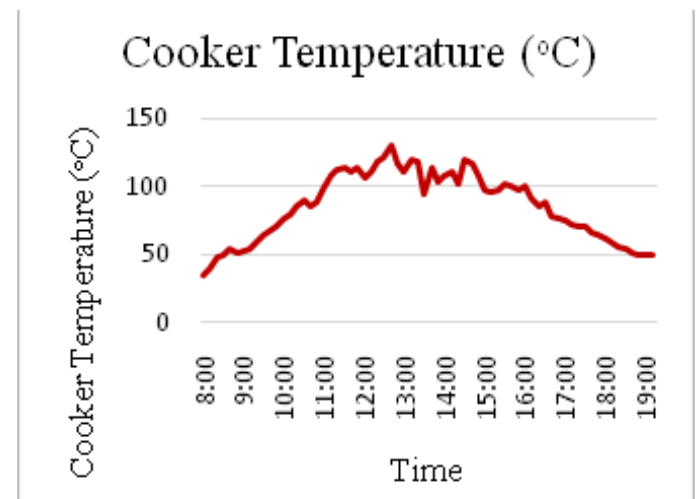


Figure 7: Temperature variation within the device under no-load

A regression model in form of Equation 12 was obtained for Cooker Temperature (T_c) in term of process parameters.

$$T_c = -126.957 + 33.082t + 0.184945I + 5.42049T_a - 0.320191V \quad \dots \dots \dots 9$$

The coefficient of determination (R^2) of the model was 91.45 %. All parameters except wind velocity and time significantly ($p < 0.05$) influenced the cooker temperature. The R^2 value was greater than 75% presented by the ASAE 2003 Standard.

The averaged time of 90.5 minutes required to boil 1.5 litre of water was observed to be close to result from Aremu (2004) in a similar study. During the water heating process, it was observed that the time that was required to raise water from ambient temperature to a temperature of 80 °C was relatively shorter than the time required to take it from 80 °C to boiling point. This was due to the increase in heat

loss as the temperature difference between the cooker temperature and the ambient temperature increases. Also, the use of a pressured pot also increased the boiling point there by making the water boils at a higher temperature.

The results obtained compares favourably with the findings of Aremu (2004), who achieved similar timings in his solar box cooker insulated with coconut coir during the wet season.

the BIS standard values on testing and reporting solar cooker performance requires that the first figure of merit (F_1) ≥ 0.12 and the second figure of merit (F_2) ≥ 0.25 , the test carried out, the solar box cooker has a First Figure of Merit (F_1) of 0.13 and a Second Figure of Merit (F_2) of 0.27 had met standard for solar cooker. The First Figure of Merit is higher than the approved value which indicates decrease in heat loss. Also, the Second Figure of Merit depicts the slower rate of increase in temperature which is advantageous when keeping food warm for long time is concerned. The results obtained for both the no-load test and the load test deplete that the presence of rock pebbles within the device as storage material and the presence of the hot water unit extended the cooking time about two hours after the noon which is a considerable amount of time, thus making the device suitable for evening meal.

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CONCLUSIONS

The study clearly revealed that

The presence of the heat storage unit made it possible to cook beyond 15:00 hours up until 18:00 hour local time and the food was homogeneously cooked. Also, t

The hot water from the dispensing unit attained a temperature of about 65°C for most days of testing at about 13:00 \pm 0:40 hours and gradually dropped to about 50°C \pm 5°C by 19:00 hours local time. The presence of available warm water helped reduce the cooking time considerably. In addition, t

The presence of the rock pebbles and hot water in the device helped to stabilize the cooker temperature consequently increasing the available energy on the heat absorber plate. It was also found that

The water taken from the hot water dispenser located in the device is sufficiently hot for most domestic use and the amount of energy required to take it to boiling point has been greatly reduced which would save cost and time. Finally, t

The cooker met the required standard in terms of F_1 and F_2 values of 0.13 and 0.27 respectively making it a recommended device for direct utilisation in cooking and water heating activities.