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Performance Evaluation of Box-Type Solar Cookers Using Different Insulation Materials

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ABSRACT

This study investigates the thermal performance of solar box cookers developed using sawdust, chicken feather, and groundnut shell, respectively as insulation materials. Stagnation tests and load tests were carried out to evaluate the cooker performance by determining first figure of merit (F_1), cooking power, standardized cooking power and the thermal efficiency of the developed cookers. The F_1 values for cookers A (which served as the control), B (sawdust), C (chicken feather) and D (groundnut shell) were found to be 0.099 °C m^2/W, 0.129 °C m^2/W, 0.114°C m^2/W and 0.111°C m^2/W, respectively. The standardized cooking power at 50^{0}C temperature difference for cookers B, C, and D were 42. 25W, 37.26W and 35. 25 W, respectively. Statistical analysis showed that the regression for cookers B and D have a good fit. Cooker C, however, has an R^2 value of less than 75%; the variation in the cooking power, therefore, cannot be explained by temperature difference. The overall thermal performance of the cookers B, C, D were reported as 25. 46%, 23.51% and 24.0%, respectively. The study concludes that effective utilization of a material with good thermal insulation property contributes significant roles in improving the cooking performance of the cooker.

Keyword: Solar cooker, Insulation material, stagnation test, cooking power, figure of merit

INTRODUCTION

Population increases coupled with increase in standard of living would lead to a high demand for energy. Majority of the country's population still use conventional fuels for preparing food (Yusuf *et al.*, 2014). Continuous use of these fuels consisting of charcoal, wood,

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kerosene, and agricultural waste has devasting effect on the environment as well as human health (Cuce and Cuce, 2013). These problems can be reduced by the use of alternative energy resources such as solar energy.

One of the most abundant, free, sustainable and environmentally friendly sources of energy is the solar energy. The solar energy reaches the earth surface from the sun through electromagnetic radiation, about $3.8 \times 10^{26} W$ of radiation is produced by the sun of which about $1.7 \times 10^{17} W$ reaches the planet earth (Yunus, 2002). Cooking as one of the applications of solar energy, is one of the most energy-consuming activity in developing countries (Panwar *et al.*, 2012). Cooking with the sun dates back to the eighteenth century (Halacy and Halacy, 1992), since then different types and configurations of the solar cooker has emerged. The solar box, being one of the most commonly used solar cooking devices, is an environmentally friendly and cost-effective cooking device for harnessing solar energy.

There is no dearth of research on the design and performance evaluations of solar box cookers. Yusuf *et al*., (2014) evaluated of the thermal performance of a constructed box type solar oven with reflector; they found out that the efficiency increases with decreasing temperature difference between plate temperature and ambient temperature, while it decreases with decrease in solar radiation. Amanuel *et al.,* (2019) experimentally investigated the thermal performance of the developed solar box cooker with different reflector configurations; they reported the highest computed value F_1 of 0.154°Cm^2/W from the cooker with tracking reflector at optimal angle. They concluded that effective utilization of all solar radiation intercepted on the reflector, and the use of cooking vessel have a reasonably good thermal diffusivity and contribute significant roles to improve the cooking performance of the cooker.

Vigneswaran *et al.,* (2017) carried out performance evaluation of a solar box cooker with varied number of reflectors; they found that the time consumed for cooking in a box type solar cooker with four reflectors is lesser compared to that of a single reflector and its overall utilization efficiency increases with increase in the cooking mass. Abdulrahim *et al.,* (2020) carried out the performance evaluation of solar oven using Kapok wool as the insulation material. They used kapok to line the oven's walls to serve as insulator; the results show that maximum stagnation temperature was 165.1°C and maximum overall daily thermal efficiency of 19.44% was achieved on a clear day test without reflector. These and many more researches have been carried out to find the performance evaluation of solar box cookers.

An important parameter in the design and performance of solar box cooker is thermal insulation. The walls of the solar oven need to be insulated in other to minimize heat loss by conduction and convection from within the cooking chamber and the walls of the cooker. Previous researchers have used paper (Uhuegbu, 2011), foam (Rikoto and Garba, 2013), glass wool (Yousif, 2012; Yusuf *et al.*, 2014), sawdust (Amanuel *et al.*, 2019) kapok (Abdulrahim *et al.*, 2020) among others. The performance of different insulation material has also been compared (Mishra and Prakash, 1984; Aremu and Akinoso, 2013; Aremu and Igbeka, 2015). This study is primarily focused on the thermal performance of developed solar box cooker using saw dust, groundnut shell and chicken feather.

MATERIALS AND METHODS

Description of the Solar Cooker Components

The developed box-type solar cooker was constructed from paperboard of 10 mm thickness. The collector of dimensions 14 cm × 18 cm ×23 cm and 252 cm^2 aperture area is made of a double-wall box of thickness 6 cm covered with a transparent glass lid. This space is filled with the insulation materials (air, which serves as the control saw dust, chicken feather, and groundnut shell) of thickness 6 cm. The top of the collector is inclined at angle of 25° in order to give the reflector enough view surface area to the sun's rays. The reflector, placed on top of the collector, focusses a considerable amount of suns ray into the collector (cooking chamber). There are two adjustable adhesive straps for manual tracking of the sun in other to get maximum amount of sun's rays.

The developed cookers were designated as follows:

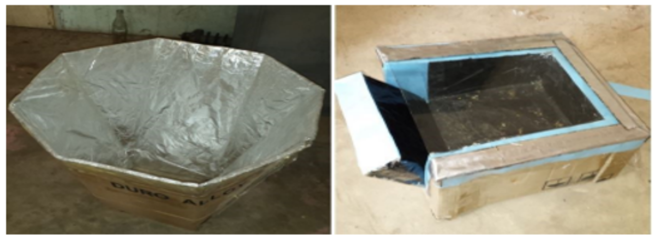
Control: Cooker A

Cooker with sawdust as insulation material: Cooker B

Cooker with chicken feather as insulation material: Cooker C

Cooker with groundnut shell as insulation material: Cooker D

The working principle of the solar cooker is simple. The solar cooker is placed directly under sun light, where the reflector concentrates the sun's rays to the collector. It heats up the cooking chamber of the cooker, the trapped heat causes a temperature raise in the oven which makes it suitable for cooking.



(a) Solar Reflector (b) Solar Collector

Figure 1 Components of The Solar Box Cooker

Experimental Set up

The experimental works were performed at the Faculty of Engineering Workshop, University of Maiduguri. Totally, two experiment for the different insulation materials, including stagnation tests and and the load tests were carried out. The experiments for the stagnation test were started at 08:45 am and continued until 04:05 pm in the month of April when the solar irradiation is at its maximum in Maiduguri; and the variables were recorded at 15 minutes interval. The load tests experiments were started at 11:30 am through 01: 40 pm and the variables were recorded in every 10-minute interval. Thermometer (Model: MTM-380SD, sensitivity 0.1^{0}C) was used to measure the ambient, the absorber plate, and the water temperature. A digital pyranometer was used to measure the solar radiation intensity.

Performance of the Solar Cooker

The performance of the solar box cooker was evaluated according to the Bureau of Indian Standards (BIS) (Mullick *et al.*, 1987; Ayoola *et al.*, 2014) by determining the performance indexes, such as the first figure of merit F_1, the cooking power P and the thermal efficiency η.

The first figure of merit, F_1, of a solar box cooker is defined as the ratio of optical efficiency to overall heat loss coefficient. It was determined from the stagnation test under no load condition using the following expression (Mullick *et al.*, 1987):

$$F_1 = \frac{T_{ps} - T_{as}}{I_s} \tag{1}$$

where T_{ps}, T_{as} and I_s are the absorber plate temperature (°C), the ambient temperature (°C), and the solar radiation on horizontal surface (W/m^2), when the plate temperature reaches the maximum, respectively. Four stagnation tests, one for each solar box with different insulation material and the other for the control, were carried out to determine F_1.

Following BIS, solar box cookers are grouped into two grades depending upon their performance. For cookers with higher thermal performance value F_1 designated as Grade A, F_1 should be greater than 0.12. Whereas, cookers with lower thermal performance value (F_1) designated as Grade B should have a F_1 value of not less than 0.11.

Cooking power, P, defined as the product of the heat capacity of water confined in the vessel and the water temperature change divided by the time interval of 600 s was calculated by the following expression (Funk, 2000):

$$P = \frac{(mc_p)_w(T_2 - T_1)}{600} \tag{2}$$

where P is the interval cooking power (W), m is the mass of water (kg), c_p is the specific heat capacity of water (J/kg ^{0}C), T_2 and T_1 are the initial and final water temperatures in every interval (°C), respectively.

The cooking power is standardized according to a model developed by Funk (2000) using the following expression:

$$P_s = \frac{P \; x \; 700}{I} \tag{3}$$

Where 700W/m^2 is taken as the standard solar radiation and I is the average solar radiation for each interval.

The overall thermal efficiency of the solar box cooker as reported by Abdulrahim *et al.* (2020) is expressed mathematically as:

$$\eta = \frac{(mc_p)_w(T_{w2} - T_{w1})}{IA_i\Delta t} \tag{4}$$

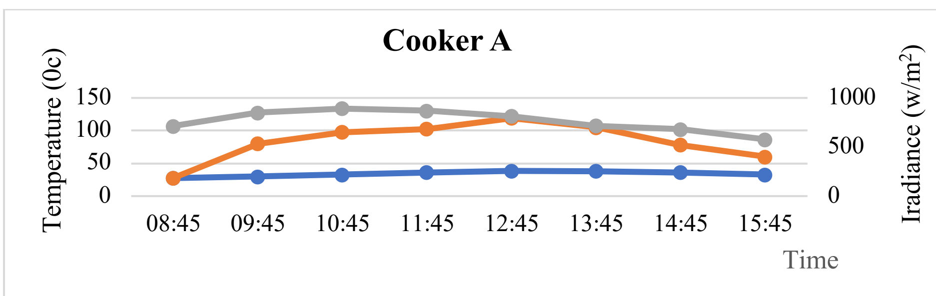
where A_i is the intercepted area of the cooker (m^2), Δt is the time interval (s), in which the water temperature rises from T_{w1} to T_{w2}, and I is the average solar radiation (W/m^2) over the time interval Δt. $T_{w1} = 60\ ^0$C and $T_{w2} = 90\ ^0$C are taken as initial and final temperature of water, respectively as suggested by the Bureau of Indian Standards. Figure 2 shows the 4 solar cookers under performance test.

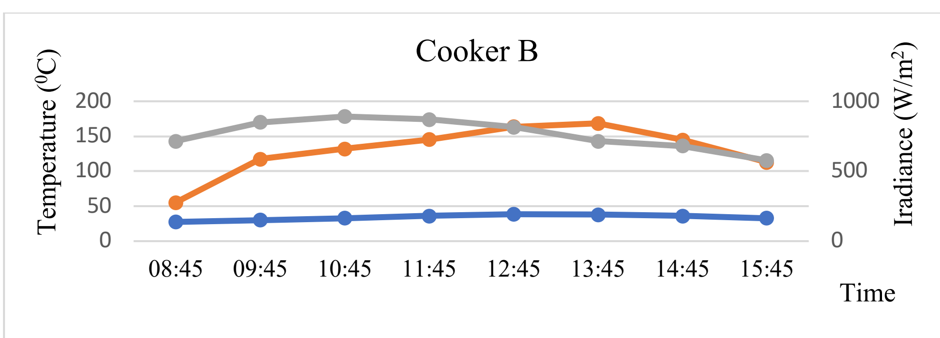
Figure 2 The Four Solar Cookers Under Performance Test

RESULTS AND DISCUSSION

Stagnation Tests

Figure 3 presents the results of the absorber plate temperature, the ambient temperature and the solar radiation intensity during the stagnation tests.





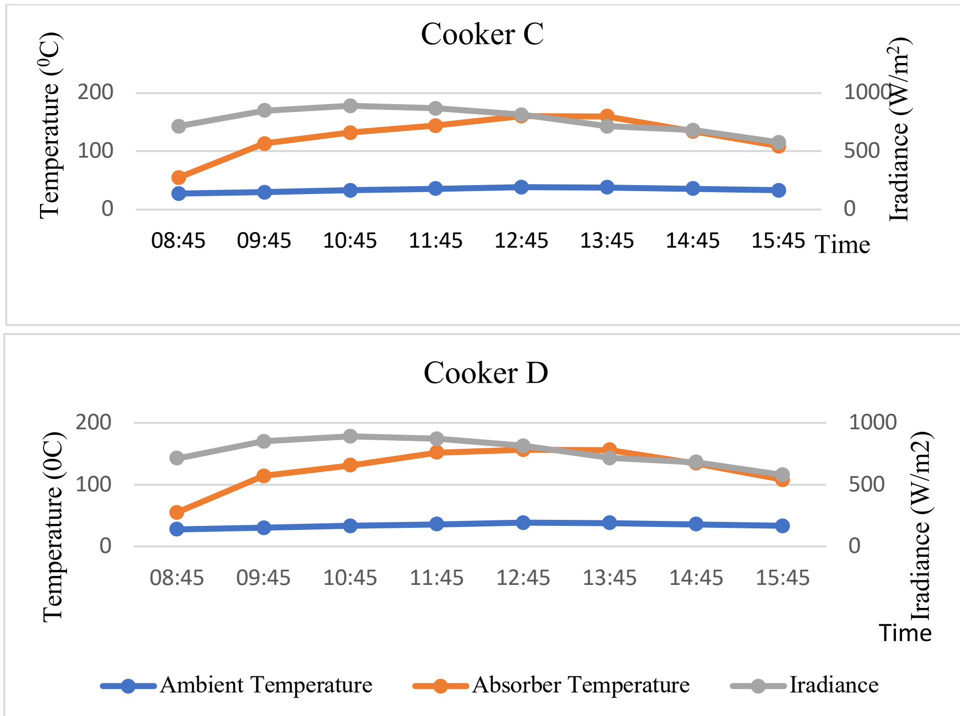


Figure 3: Thermal Performance Curve of The Cookers Under Stagnation Test

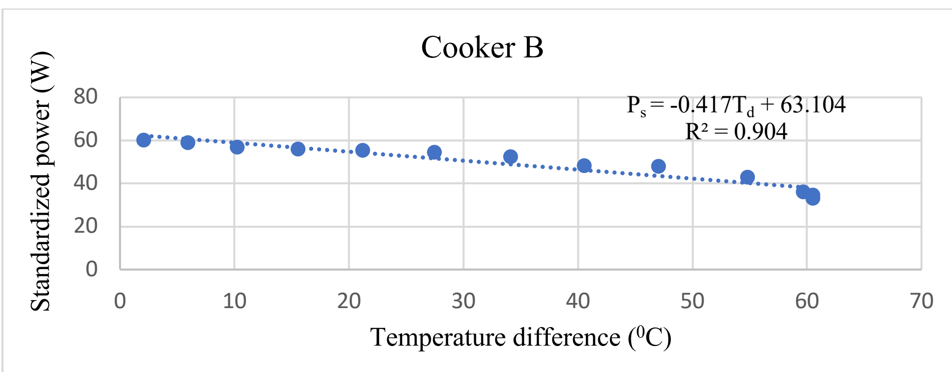
The maximum absorber plate temperature which was achieved for cooker A at 12:45 local time was 119.0 °C. The corresponding ambient air temperature and solar radiation were 38.5 °C and 815 W/m^2, respectively. The computed value F_1 was 0.099 °C m^2/W. This value falls below the standard by BIS and therefore, the performance of the cooker was poor. This may be due to the relatively poor insulating property of air. For cooker B, the maximum absorber temperature of 130.5°C was attained at 13:45 local time with a corresponding ambient temperature of 38.0 °C and solar radiation of 715 W/m^2. The computed F_1 was 0.129 °C m^2/W. Thus, performance of this cooker was good and it is grouped under grade-A cooker. The maximum absorber plate temperature of 123.5°C for cooker C was achieved at 12:25 local time. The corresponding ambient air temperature and solar radiation were 38.0 °C and 750 W/m^2, respectively. The computed value F_1 was 0.114°Cm^2/W. The thermal performance of this cooker was low; and is thus, under grade-B cooker. For cooker D, the maximum absorber temperature of 121 °C was attained at 12:05 local time with a corresponding ambient temperature of 38.5 °C and solar radiation of 7450 W/m^2. F_1 was computed to be 0.111 °C m^2/W. the cooker is grouped under grade-B. Therefore, by this result, it implies that sawdust is a better insulation material as compared to chicken feather and groundnut shell.

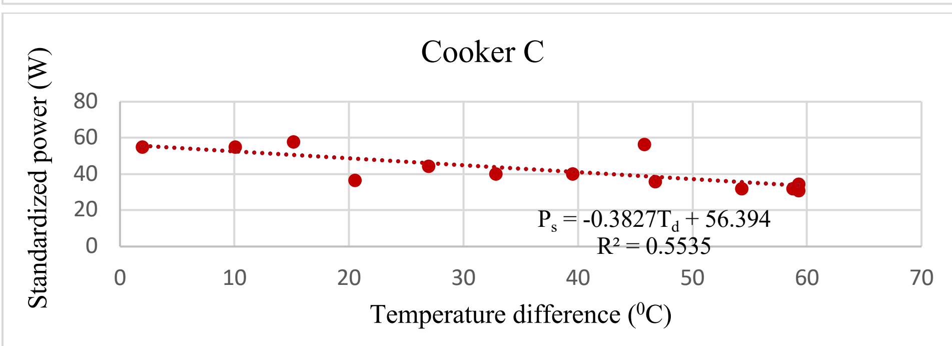
Cooking Power

The load tests were carried out in order to evaluate cookers' performance in terms of cooking power and thermal efficiency. The experiments were carried out by loading a 1 kg of water in a vessel and lasted for 3 hours. The tests were applied to determine the cooking power of Cooker B, C and D.

The cooking power at 10-minute interval and standardized cooking power of the cookers were computed from the experimental data and the standardized cooking power was plotted against temperature difference for all cookers, as shown in Figure 4.

The relationship between the standardized cooking power and the temperature difference between the ambient air and water was found using linear regression. The coefficient of determination R^2 of the linear regression indicates the proportionate relationship between cooking power and temperature difference.





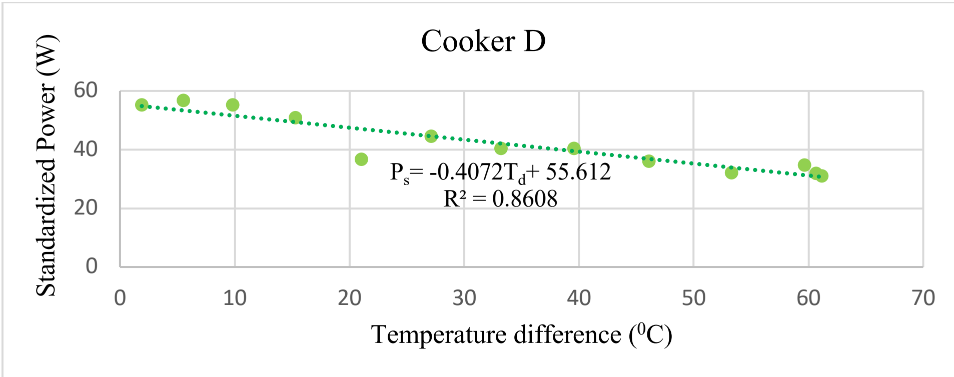


Figure 4 Standardized Cooking Power and Linear Regression Curve of Cooker B, C, D

The coefficients of determination (R^2) or proportion of variation in cooking power attributed to variation in temperature change should be better than 75% (Funk, 2000). The values for R^2 for cooker B, C, D are 0.904 (90.4%), 0.5535 (55.35%) and 0.8608 (86.08%) respectively. Table 1 compares the three cookers in terms of cooking power regression equation.

Table 1: Comparison of cookers with level of intercept and slope

Solar cooker	Cooking power regression equation		Adjusted cooking Power (W) at 50^0C T_d
	Intercept (W)	Slope (W/^{0}C)	
B	63.104	-0.417	42.254
C	56.394	-0.3827	37.259
D	55.612	-0.4072	35.252

Thermal Efficiency

The thermal efficiency of the cookers was computed using equation (4). The chosen initial and final temperatures of water were 60.5 °C and 89.5 °C, respectively. All the cookers maintained the cooking temperature for more than an hour. The thermal efficiency for cooker A, B, C and D are 18.51%, 25. 46%, 23.51% and 24.0% respectively.

CONCLUSION

The study focused on the investigation of thermal performance of the developed solar box cooker using three different insulation materials. Stagnation tests and load tests were carried out to evaluate the cooker performance by determining F_1, cooking power, standardized cooking power as well as the thermal efficiency of the developed cookers. The F_1 values for cookers A, B, C and D were found to be 0.099 °C m^2/W, 0.129 °C m^2/W, 0.114°C m^2/W and 0.111°C m^2/W respectively. Cooker A did not pass the standard test procedure as its value of

F_1 was below the standard. The standardized cooking power at 50 ^{0}C temperature difference for cookers B, C, and D, are 42. 25W, 37.26W and 35. 25 W respectively. Cooker C, however, has an R^2 value of less than 75%; the variation in the cooking power, therefore, cannot be explained by temperature difference. The regressions for cookers B and D have a good fit but one could argue that the relationship is not linear. This could be due to a small number of experimental observations or some parameters beyond control. The overall thermal performance of the cookers B, C, D were reported as 25.46%, 23.51% and 24.0% respectively.

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Conflict of Interest:

There is no conflict of interest.

Author Contribution

Ishaq, Muhammad Idriss: Conceptualization, Methodology, Validation, Writing – original draft, Writing, Data curation. Oluwole, Fasiu Ajani: Supervision, Writing – review & editing. Amulah, Nuhu Caleb: Writing – original draft, Writing – review & editing, Data curation, Formal analysis.

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