

Performance Evaluation of a Building Integrated Solar Cooker with Asymmetric Compound Parabolic Concentrator for Indoor Cooking Application

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ABSTRACT

Nigeria faces an acute shortage of conventional energy sources, relying heavily on fossil fuels for cooking, which poses significant health and environmental risks. Solar cookers have emerged as a promising alternative. However, existing solar cookers have limitations, including exposure of users to direct sunlight, low utilization efficiency, and they are predominantly designed for rural and community environments, making them less suitable for urban settlement. This study evaluates the performance of a building-integrated solar cooker (BIS) with an asymmetric compound parabolic concentrator (CPC) for indoor cooking. Experimental tests achieved maximum stagnation temperatures of 126.9°C and 124.8°C on two consecutive days. Water heating tests showed a boiling times of 1 hour 40 minutes and 2 hours for 1.5kg and 2kg of water, respectively. The cooker's figures of merit (F1 and F2) values meet recommended standards, confirming its functionality. Successful cooking of eggs, noodles, and rice demonstrates its potential for sustainable indoor cooking. From the regression analysis, standardized cooking power of 513 W at a temperature difference of 50 °C were estimated using the regression equation and coefficient of determination (R^2) were found to be 0.98, exceeding the minimum requirement of 0.75. This indicates a well-fitting regression model for the system. This study addresses the limitations of existing solar cookers highlighting its potential as a viable alternative to conventional energy sources for sustainable indoor cooking and advances solar-thermal technology for urban contexts, aligning with the United Nations Sustainable Development Goals.

Keywords: Building integrated solar cooker, compound parabolic concentrator, indoor cooking and thermal performance.

1.0 INTRODUCTION

Renewable energy is a type of energy derived from natural sources such as wind, solar energy, wave tidal, geothermal heat and biomass, etc. renewable energy contributes approximately 19.2% of the world energy consumption and 23.7% of electricity generation (Arnold, 2019). Renewable energy is currently the most preferred energy source, as it provides a solution to rising energy demand while addressing issues such as environmental pollution, reserve constrains, and energy cost. Having advantage like endless supply and nearly low environmental impacts, renewable energy like, solar energy has become the major focus of interest to the researchers and has been utilized and studies comprehensively more and more for a long time (Khan, 2020). In Nigeria, where there iacute shortage of conventional source of energy, Nigerian Electricity Regulatory commission (NERC, 2019) is exploring the renewable energy resources available for sustainable development.

They estimated an annual average of daily solar radiation to vary from 7KW/m²/day in the northern border regions to 3.5KW/m²/day in the coastal region of south and an annual average daily sunshine hour to vary from as high as greater than 8hrs/day in the northern border region to as low as less than 6hrs/day in the coastal Regions of south (Mohammed et al, 2018).

Therefore, northern Nigeria with direct solar irradiance (DNI) above 4.1KWH/m²/day is considered suitable for concentrated solar application because of its abundant sunshine and relatively open terrain.

Cooking is a fundamental activity for human survival and sustenance, accounting for roughly 90% of domestic energy consumption in developing countries (Newell et al., 2019). The majority of rural households rely on conventional fuels for heating and cooking, with firewood accounting for nearly all of the fuel used in village kitchens. Each year, about 16 million hectares of forest are burned as cooking fuel, resulting

in three million deaths worldwide due to toxic pollution from the burning of this biomass fuel (WHO, 2020). The majority of people in developing countries cook their food with biomass as their primary energy source. Nearly 730 million people in sub-Saharan Africa countries rely on biomass as a primary energy resource (Sajjadi et al, 2018). According to World Bank.

In Nigeria, biomass accounts for over 80% of Nigeria's energy consumption (NBS, 2020). According to Overend. The main reason for the consumption of biomass in sub-Saharan countries is for cooking purposes (IEA, 2019). The extensive utilization of these energy sources leads to significant health and environmental issues (Sambo, 2021). In addition to contributing to global warming and deforestation, the combustion of these fuels emits harmful fumes, putting users at risk. According to United Nation Sustainable Development goals (SDG) report 2022, their about 4 billion people still relied on inefficient and polluting cooking systems in 2020. Indoor air pollution is responsible for approximately 1.6 million deaths annually, predominantly affecting women and children (WHO, 2020). While electric cookers are efficient in providing thermal energy, their widespread availability remains limited in rural areas of many developing nations. Additionally, the high expenses associated with electricity generation and distribution, coupled with inconsistent power supply commonly observed in developing economies, present significant drawbacks (Ugochukwe C.O et al, 2019). Therefore, solar cookers have emerged as a promising alternative energy source for cooking, offering environmental benefits.

1.1. Solar Cookers

Solar cooker is a cooking device that cooks' food by absorbing solar thermal energy in form of solar radiation. The solar cooking saves a significant amount of conventional fuels. Worldwide, today there are about 60 major designs and more than 100 of variations. Many countries around the globe use solar cookers. Its usage increases as the prices of cooking fuel such as LPG, electricity, coal and kerosene increased. Solar cookers have attracted the attention of many researchers so far and as result of continuous research, the different types of solar cookers have been designed, developed and tested all over the world. Currently, there is a competition to manufacture efficient and cheap solar cookers (Aramesh, et al, 2019). There has been a considerable interest recently in the design, development and testing of various types of solar cookers (Singh, 2020).

1.2. Different Types of Solar Cooking System

There are various types of solar cookers that have been fabricated from previous studies this include box-type solar cooker, panel solar cooker, parabolic dish, parabolic trough and evacuated solar cooker (Singh, 2020). A common solar box cooker consists of an

insulated box with a transparent glass or plastic cover that allows solar radiation to pass through. Solar radiation is absorbed by the inner part of the solar box cooker while the transparent cover prevents solar radiant energy from leaving the interior of the box through the greenhouse effect (Wentzel, 2019). In some solar box cookers, the interior of the box is painted black to maximize the absorption of solar radiant energy in order to increase the temperature of the cooking vessel placed inside. The insulated box is connected to reflectors which direct more solar radiation into the cooking vessel, thus increasing its cooking efficiency. The appeal of solar box cookers over other types of solar cookers include the fact that they are easy to construct, they are user-friendly and safe to use, they require limited attention during operation, they utilize both the direct and diffusion components of solar radiation and no solar tracking is required (Kaushik et al, 2019).

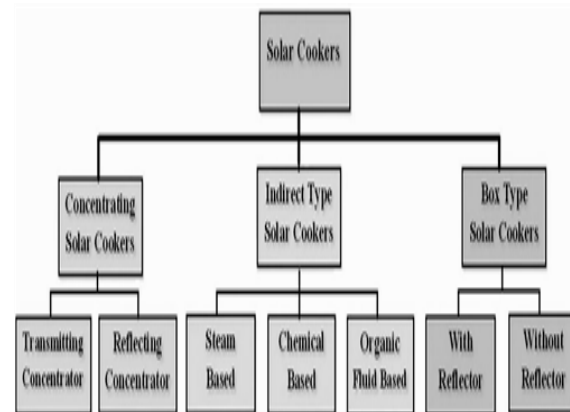


Figure 1. Classification of solar cookers

The major limitations of existing solar cookers for widespread adoption in urban settings include exposure of users to direct sunlight, low utilization efficiency, and technical complexity and they are predominantly designed for rural and community settings, rendering them less suitable for urban environments with limited available space. Furthermore, the existing research primarily emphasizes energy efficiency, disregarding the significance of exergy efficiency as a comprehensive performance metric for solar-thermal systems, which indicates the quality of energy converted into a useful form (Chandel, 2020). The urgency to address energy and environmental challenges associated with traditional cooking methods in Nigeria's rural and urban environments justifies this research. The present study aims to conduct experimental investigations to enhance the performance of a building-integrated solar cooker. This involves incorporating a compound parabolic concentrator for enhanced performance. The goal is to create an efficient indoor cooking system that prioritizes both energy and exergy efficiency. This research aims to overcome current solar cooker

limitations and advance solar-thermal technology in urban contexts by developing a building integrated solar cooker that is affordable, readily available, and suitable for indoor cooker. Moreover to provide an innovative solution that promotes sustainable cooking practices, reduces greenhouse gas emissions, and

mitigates deforestation. Moreover, this research aligns with the United Nations Sustainable Development Goals, specifically Goal 7 (Affordable and Clean Energy) and Goal 11 (Sustainable Cities and Communities) (SDG, 2022).

2.0. MATERIALS AND METHODS

2.1 Measuring Instruments

Various types of instruments used in this study are listed in Table 1. and also discussed below:

Table 1: Measuring Instruments with Specifications

Instruments	Model Numbers	Manufacturers
Data logger thermometer	SD-497	Reed
Digital thermometer	Kat.Nr. 30.5015	TFA Dostmann/Wetrheim
Thermocouple wires	T-type	
Pyranometer	SL101	Di-LOG
Digital Scale	SF-400	Dhaare Healthcare Kitchen

2.2 Design Specification of the Building Integrated Solar Cooker

The existing box-type solar cooker design was re-design and transformed it into a functional building integrated solar cooker. This modification process takes into account various factors, including shape, size, materials, thermal insulation, absorber type and design, with primary objective of maximizing heat capture and retention. Furthermore, the design was incorporated with asymmetric compound parabolic concentrator (CPC) to further enhance its capacity for capturing maximum solar radiation.

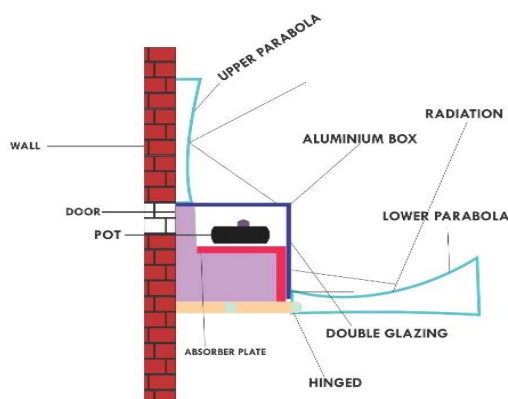


Figure 2: Schematic Diagram of Building Integrated Solar Cooker

An aluminium box of area 0.901m^2 was fabricated using $\frac{3}{4}$ aluminium pipe, 4mm transparent glass, nuts screw, insulation rubber and hinges. An aluminium absorber box with an area of 0.506m^2 was casted and

coated black to effectively absorb both direct and reflected solar radiation. To ensure proper insulation and allow radiation to pass through, a 4mm thick transparent glass material was employed. This material serves as the top and underneath cover of the cooker, as well as an insulating layer. $0.7\text{m} \times 0.4\text{m}$ asymmetric compound parabolic concentrator was constructed using stainless steel and aluminium foil. This concentrator is hinged at the top and bottom of the cooker, serving as the upper and lower concentrators. To support the solar cooker and provide stability, an iron stand with a length of 0.7m was fabricated. The solar cooker was integrated into a building which was inclined at an angle of 13° (taking into account the latitude of the study area which is Sokoto Energy Research Centre with $13^\circ 07' 60.0'' \text{N}$ $5^\circ 12' 13.8'' \text{E}$ coordinate). This choice ensures that the sun's rays will be closest to normal incidence average over one year.



Figure 3. Front side of the BIS Cooker

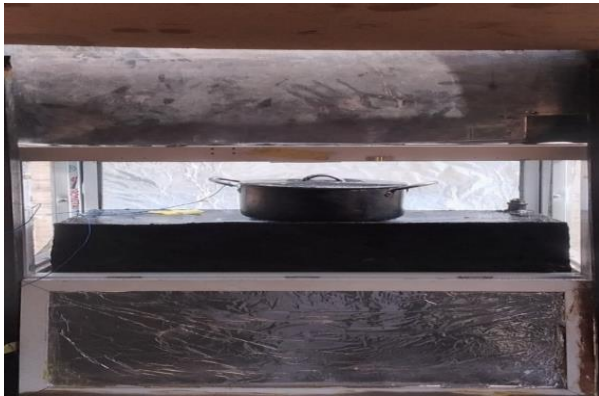


Figure 4. Back side of the BIS Cooker

2.3 Experimental Set-Up

(a) Stagnation Temperature Test (1st Figure of Merit F_1)

This was used to determine the thermal performance of the solar cooker under no load condition (first figure of merit F_1). The cooker was operated without cooking (under no load) to determine the maximum possible temperature attainable at a particular point in time. The solar cooker was positioned to face the direction of the sun at about 60° N latitude. The cooker's orientation was in such that the compound parabolic concentrators (reflectors) reflect the sun's rays directly into the absorber box. Thermocouple wires were connected to a data logger thermometer and placed on the cooker's absorber surface and the solar cooker internal air to measure their temperatures. The cooker was then securely shut. The ambient temperature around the cooker was monitored using a digital thermohygrometer, and the solar insolation of the sun's rays was measured using a Pyranometer. Measurements were taken after every ten minutes until the temperature reached maximum stagnation. This was repeated for two days (Aremu, 2019).

(b) Water Boiling capacity Test (2nd Figure of Merit F_2)

This was carried out to determine the time it takes the solar cooker to boil a known volume of water (second figure of merit F_2). However, 1.5 kg of water was loaded into the cooker. Thermocouple wire type-k was fixed to run through a small hole made on the pot lid placed within the pot and not touching the base of the pot. Water temperature inside the pot, ambient temperature, absorber temperature and solar radiation were recorded at intervals of ten minutes. The experiment was carried out until water temperature reached 97°C . This experiment was repeated for three days which is the method that have been previously used by several researchers (Ugochukwu *et al*, 2019).

(c) Cooking Evaluation Test.

This was carried out to determine the time it takes solar cooker to cook various type of foods (eggs, noodles, white rice). Weight meter was used to measure the weight of food items in kg. An aluminium cooking pot of 400 mm diameter \times 200 mm height was used to evaluate the cooking performance of the cooker. Where in the first test 3 pieces of eggs 70 grams each were boiled in 0.5 kg of water, taking note of the temperature range and time it took the eggs to be cooked. The eggs were considered to have been cooked when the temperature of the water reached 82°C . In the second cooking test 240grams of noodle and 0.25kg of water was cooked taking into account the time it takes the cooker to cook the noodle and in the third cooking test a 500grams of white rice with 0.51kg of water was cooked.

The cooking was monitored until when the food temperature reached 97°C . However, the system was heated up to the minimum cooking temperature range ($72^\circ\text{C} - 82^\circ\text{C}$) before loading the cooking materials into the system (USDA, 2020). Additionally, the amount of time it took to cook the cook was recorded. Water temperature inside the pot, absorber plate temperature and wind speed was taken with the aid of thermocouple wires, digital data logger thermometer and anemometer.

(d) Determination of figure of merits

The procedures for testing the solar cookers depend on climatic parameters. The evaluation of the cookers was extended to parameters that are independent of climatic factors from which two figures of merit denoted by F_1 and F_2 was determined (Singh *et al*, 2020) according to Funk, 2000. The first figure of merit (F_1) was obtained by monitoring the time/temperature profile of an unloaded box solar cooker set under the sun. The highest temperature attainable inside the cooker with the corresponding ambient temperature and the corresponding insolation were noted and the first figure of merit was obtained from Equation (1).

$$F_1 = \frac{T_{ps} - T_{as}}{I_s} \dots \dots \dots (1)$$

where; F_1 is the first figure of merit, T_{ps} is the stagnation temperature ($^\circ\text{C}$)

T_{as} is the ambient temperature ($^\circ\text{C}$), I_s is the solar insolation at stagnation (W/m^2)

The second figure of merit was obtained from the water boiling test using Equation 2. (Mullick *et al*, 1996).

$$F_2 = \frac{F_1(Mc)w}{A(t_2 - t_1)} \log_e \left\{ 1 + \frac{T_{w1} - T_{as}}{F_1 G} \right\} \left[1 + \frac{T_{w2} - T_{as}}{F_1 G} \right] \dots \dots \dots (2)$$

where; F_2 is the second figure of merit, M is the mass of water (kg), C_w is the specific capacity of water ($\text{J}/\text{kg}^\circ\text{C}$), $t_2 - t_1$ is the time taken for water to boil from T_{w1} to T_{w2} (sec) T_a is the average ambient temperature

over time period $t_2 - t_1$ ($^{\circ}\text{C}$), G is the average solar radiation over a time period $t_2 - t_1$ (W/m^2), T_{w1} is the temperature of water at time t_1 ($^{\circ}\text{C}$), T_{w2} is the temperature of water at time t_2 ($^{\circ}\text{C}$)

(e) Linear Regression Analysis

The results obtained from the experiment was analysed on Mini Tab 2017 statistical software to obtain the standard cooking power using liner regression. The standardized cooking power, P_s (W), was plotted against the temperature difference, T_d ($^{\circ}\text{C}$), for each time interval. A linear regression of the plotted points were used to find the relationship between cooking power and temperature difference in terms of intercept, a (W), and slope, b ($\text{W}/^{\circ}\text{C}$):

$$P_s = a + b \times T_d \dots\dots\dots (3)$$

3.0 RESULTS AND DISCUSSION

3.1 Stagnation Temperature for Solar Cooking Application (1st Figure of Merit F_1)

The first figure of merit (F_1) was attained through the stagnation temperature test of the building integrated solar cooking system. The test was conducted under variable solar radiation measured in W/m^2 . The results of the (stagnation) tests for two different days are shown in Figure 2 and 3, which shows the variations of the system temperatures until the maximum stagnation conditions are achieved. The tests was conducted on 18/04/2024 and 23/04/2024. Both tests have attained a maximum stagnation temperatures of 126.9°C and 124.8°C for a period of 4 hours 50 minutes and 4 hours 40 minutes respectively at an average ambient temperature of 39.9°C and 31.6 at corresponding solar radiation of $821\text{W}/\text{m}^2$ and $817\text{W}/\text{m}^2$ respectively. Similar findings were reported by Aremu (2019) who obtained an average insolation of $895\text{W}/\text{m}^2$ at temperature of the absorber plate ranging from 108°C - 124°C while the ambient temperature was 32°C - 37°C .

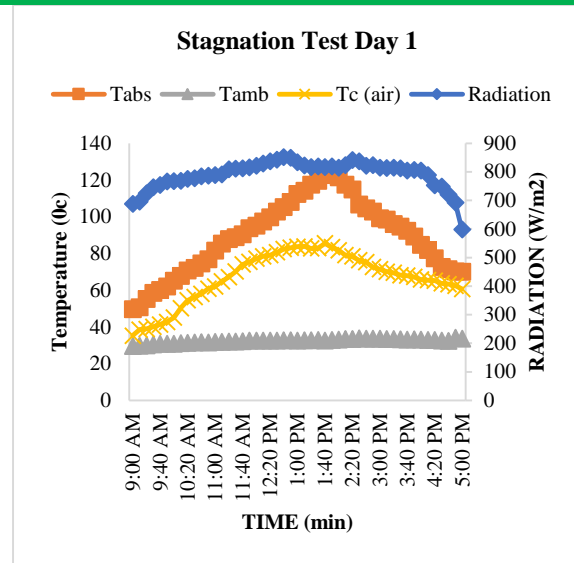


Figure 2. Variation of Temperature and Radiation during Stagnation Test (F_1)

A minimum temperature of 82°C is needed for the system to function for cooking purposes (Garba, 2022). In the F_1 stagnation test evaluation criterion, a minimum of 0.12 is needed for the cooking system to meet the cooking temperature. A high value of F_1 indicates that the system has high optical efficiency and a low heat loss factor (Aremu, 2019). Therefore the first figure of merit (F_1) was calculated as follows;

$$F_1 = \frac{T_{abs} - T_{amb}}{I_s} = \frac{126.9 - 33.1}{814} = 0.121$$

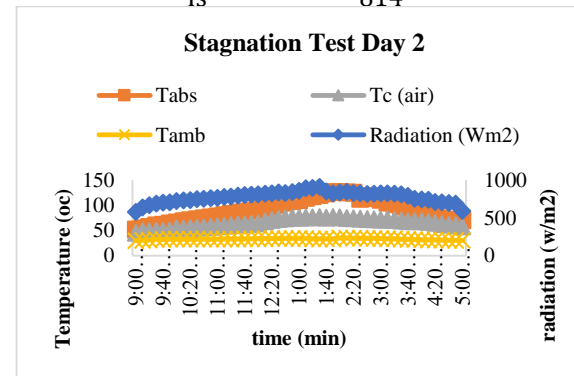


Figure 3. Variation of Temperature and Radiation during Stagnation Test (F_1)

Where T_{abs} is the absorber temperature ($^{\circ}\text{C}$), T_{amb} is the ambient temperature ($^{\circ}\text{C}$), and I_s is the solar radiation (W/m^2). Therefore, using the F_1 equation, the system has passed the F_1 evaluation criterion.

3.2 Water Boiling Test (2nd Figure of Merit F_2)

The water boiling test was conducted under variable solar radiation level with aluminium pot as a cooking utensil on 30/04/2024 and 07/05/2024. On the first day 1.5kg of water with an initial water temperature of 36.40°C took 1 hours 40 minutes to reach a boiling point at 98.7°C and took exactly 2 hours to reach

boiling point on the second day for 2kg of water to reached 97.1°C as shown in figure 4.5 and 4.7 respectively. This time is high than the value reported by Aremu (2019) in his study design and experimental testing for a building integrated box type solar cooker reported that 1.5kg of water boiled at 90 minute at an average temperature of 90.3°C. In the second figure of merit F_2 for water heating test evaluation criterion, a minimum of 0.24 was needed for the solar cooking system to meet the cooking temperature (Mullik *et al.*, 1987). Using equation (9), the second figure of merit F_2 for day1 and day2 were calculated to be 0.249 and 0.277 respectively. This value compared favourably with the ASAE value 0.25 according to (Funk, 2002), a high value of F_2 indicates that the system has high heat exchange efficiency. (Figure 4)

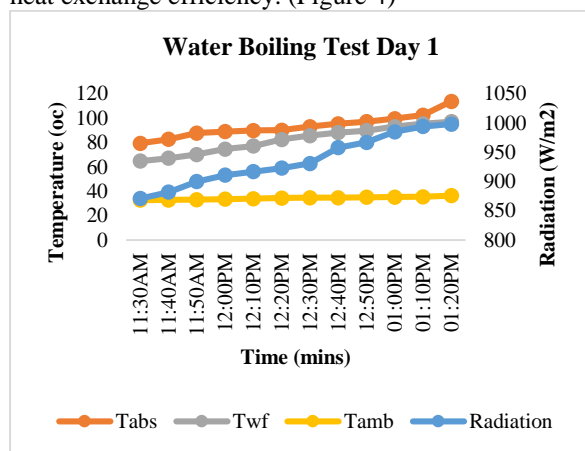


Figure 4: Temperature Variations during Water Boiling (F_2) Test

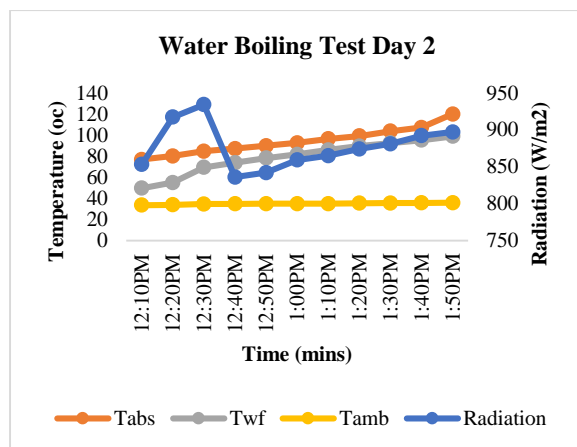


Figure 5: Variations of Temperature and Solar Radiation during Water Boiling Test

The value of the figures of merit agrees with the standard values of $F_1 \geq 0.12$ and $F_2 \geq 0.25$ (BIS Standard 1993).

Aremu (2019) carried out a similar study, and determined the figures of merits of five different solar cookers over three years. The F_1 values of the five solar

cookers that were put to test ranged from 0.11 to 0.15 for first year, from 0.092 to 0.124 for second year, and from 0.087 to 0.103 for third year. In the first, second and third year, the values of F_2 varied from 0.33 to 0.44, 0.22 to 0.66, and 0.020 to 0.025, respectively.

3.3 Sample Cooking Evaluation Tests

Eggs Cooking Test

Sample cooking evaluation test was carried out using same aluminium pot. Two pieces of eggs weighing 0.13kg were boiled in 0.6kg of water which was cooked under a variable solar radiation as above. The egg was cooked in a temperature ranging from 41.2 °C to 88.2 °C in 90 min with a maximum absorber plate temperature of 107 °C as shown in Figure 6

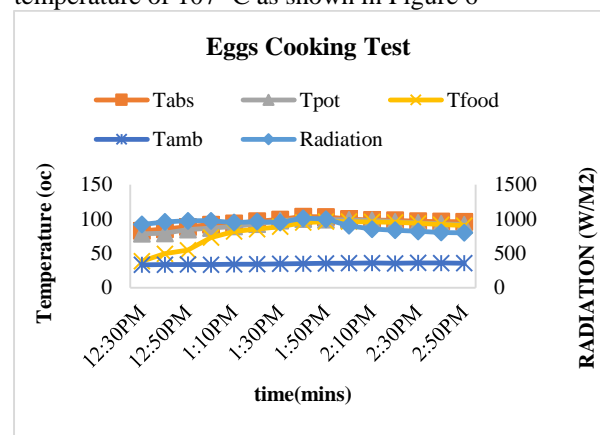


Figure 6: Eggs Boiling Performance Test

3.4 Controlled cooking test (140grams of noodle with 120grams of water)

140g of noodle with 120g water was cooked in 40 minutes with temperature ranging between 42.5°C to 88.6°C and a maximum absorber and pot temperatures of 97.3 and 92.1 respectively as shown in figure 7. Previous research by (Aremu, 2019) reported that a noodle of 200g cooked at 60 minutes. Also, Akinoso (2019) reported similar time of 34 minutes for 70g of indomie noodles.

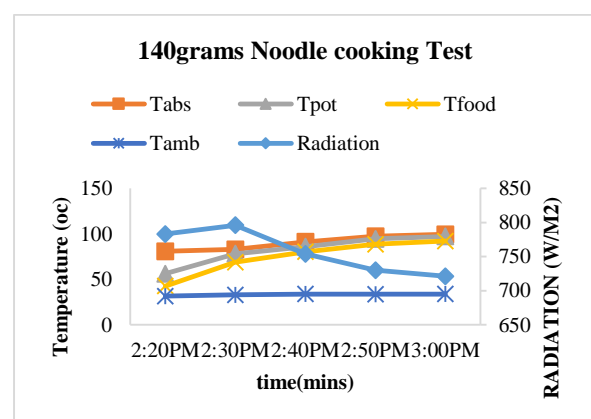


Figure 7: Variations of Temperature during Noodles Cooking Test

3.5 Controlled cooking test (500grams of local rice with 800grams of water)

Controlled cooking evaluation test was carried out. It took 2 hour 20 minutes (140 minute) to cooked 500 grams of local rice in 800 grams of water within a temperature range of 49.2°C to 96.1°C with a maximum absorber and pot temperatures of 103°C and 99.8°C respectively as shown in figure 8 below. A similar cooking test was carried out by (Garba, 2021). 0.5kg of Parboiled basmati rice was cooked in 0.70 kg of water and cooking was achieved in three hours within a temperature range of 82 °C to 95 °C with a maximum cooking pot temperature of 95 °C. Aremu (2019) also reported that rice of 300g was cooked at 180 minutes at an average insolation of 912 W/m²

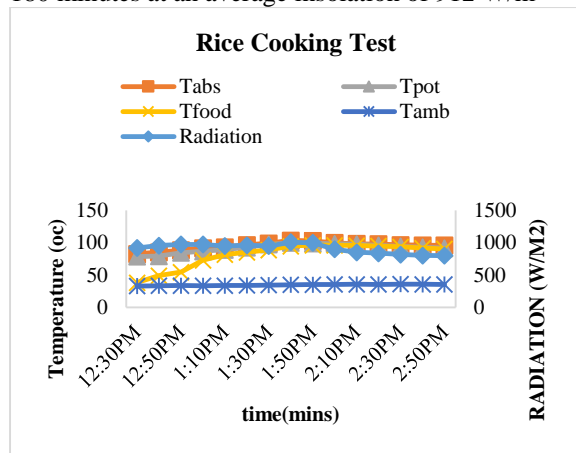


Figure 8: Variations of Temperature and Solar radiation during Cooking test

3.6 Cooking Power and Standardize Cooking Power

The cooking power (P_c) and the standard (P_s) cooking power of the solar cooker were calculated for each time interval using equation (1) and (2) respectively. The average cooking power and standardize cooking power were determined during the water heating evaluation test to be 396.6 W and 312.5 W respectively as shown in figure (9).

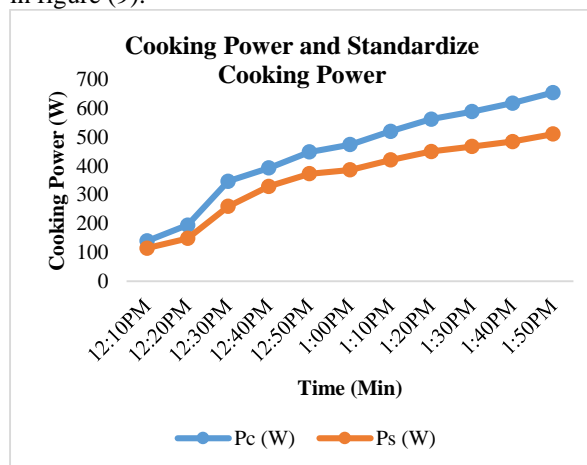


Figure 9: Variations of Cooking Power and Standardize Cooking Power

3.6 Linear Regression Analysis

Linear regression analysis was conducted using the result obtained. The standardized cooking power, P_s (W), was plotted against the temperature difference, T_d (°C), for each time interval. A linear regression model were used to find the relationship between cooking power and temperature difference in terms of intercept, a (W), and slope, b (W/°C). The coefficient of determination R^2 attributed to the relationship found by the regression is 0.985 at the p-value 0.000 which is less than the alpha-value 0.05 at 95% confidence level. According to ASAE (S580:2000) and BIS (IS1329:2002) standard the value of R^2 should be greater than 0.75, therefore the estimated value of R^2 satisfied the standard. For a single measure of performance the regression equation obtained from the regression analysis were used to calculate standardize cooking power P_s (W) at a temperature difference of 50°C. The regression model was fit for the determination of standardize cooking power of the solar cooking system which established standardize cooking power to be 513.2 W as shown in figure 10 below.

$$P_s = a + b \times T_d \dots \dots \dots (4)$$

$$P_s(W) = 43.7 + 9.390 \times 50 = 513.2 W$$

Where, the Intercept of the graph $a = 43.7$, Slope $b = 3.39$, Temperature Difference $T_d = 50$ °C

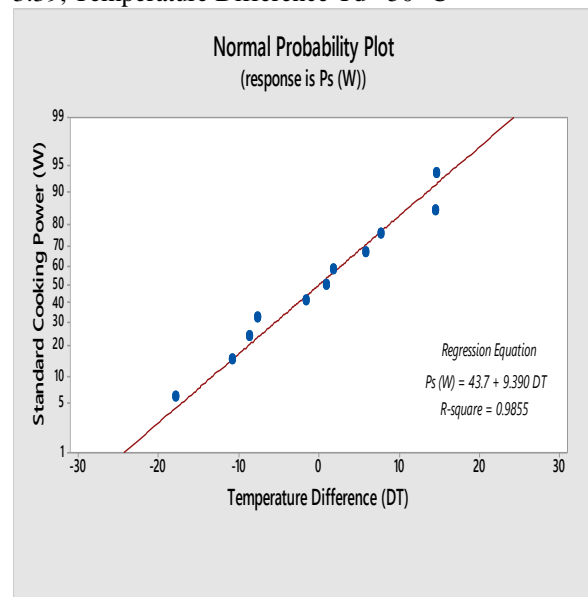


Figure 10: Linear Regression Plot of Standardize cooking Power against Temperature Difference

4.0 CONCLUSIONS

This study experimentally tested a Building Integrated Solar (BIS) cooker and evaluated its performance through stagnation, water heating, and cooking tests. The results demonstrate the feasibility of incorporating a BIS solar cooker into a kitchen wall facing the sun's

direction, harnessing energy without leaving the building. The cooker's efficiency and effectiveness were enhanced by incorporating a compound parabolic concentrator (CPC) to concentrate heat energy from the sun to the cooker box cavity. The first figure of merit (F1) was determined for tests conducted on two different days, April 18 and 23, 2024. Both tests achieved maximum stagnation temperatures of 126.9°C and 124.8°C, respectively, for a period of 4 hours and 50 minutes and 4 hours and 40 minutes, respectively, at average ambient temperatures of 39.9°C and 31.6°C, and corresponding solar radiation of 821 W/m² and 817 W/m², respectively. The resulting F1 values were 0.121 and 0.129 m²C/W, respectively, which fall within the recommended range of 0.12-0.16 m²C/W for a functional solar cooker.

The second figure of merit (F2), based on the full load test, gauges heat exchange between the cooker and food. Water heating tests conducted on April 30 and May 7, 2024, yielded F2 values of 0.249 and 0.277, respectively, which are within the suggested range of 0.24-0.49 for a functional cooker. Solar cooking tests demonstrated the cooker's ability to boil eggs, noodles, and rice efficiently. Regression analysis estimated standardized cooking power to be 513 W, with a coefficient of determination of 0.98, indicating a good fit of the regression model.

Furthermore, this study confirms the potential of the BIS solar cooker as an efficient and effective cooking solution, suitable for building integration and harnessing solar energy for cooking purposes

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