Design And Experimental Testing For A Building Integrated Box Type Solar Cooker

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***Abstract*—The technology of solar cooker has been adopted over the years however, the major constraint is the time spent and exposure to the environmental temperature while monitoring the cooked food since most solar cookers are outdoor. Thus, there is need to design a box type solar cooker incorporated into conventional kitchen. Thus, the main objective of this research was to design, construct and evaluate the performance of a low cost building integrated box type solar cooker. The performance of the indoor cooker was evaluated without load (Stagnation test), and with load (water boiling test and controlled cooking test). The stagnation temperature ranged between 54.02℃ and 80.72℃ for the air inside the pot, 72.31℃and 96℃ for absorber plate temperature and 31.4℃ and 43.89℃ for ambient temperature reading. Water boiling test was carried out using 1 litre of water and 1.5 litres of water and the average temperature recorded ranged from 69.8–78.3℃and 76.2–80℃ at an average time of 90 and 105 minutes for 1 and 1.5 litres of water respectively. The corresponding figure of merit was determined for both stagnation and water boiling test. Controlled cooking test was done by cooking Jollof rice (300g) which was properly cooked in 180 minutes, indomie noodles (147g) was well cooked at 105 minutes and eggs (two pieces) was cooked at 95 minutes. The indoor solar cooker was designed, constructed and was then experimentally tested in term of stagnation, water boiling and cooking test**

Keywords—solar cooker, stagnation test, water boiling test, control cooking test, figure of merit and figure of merits

I. INTRODUCTION

A solar cooker is a smart cooking device that collects sunlight and converts it to heat directly. By eliminating the step of converting to electricity back and forth, a high-performance solar cooker can convert more than 80% of the incoming sunlight into heat. Using solar cookers and similar heating devices at home helps cut down the energy cost and reduces the carbon emission from using gas or fossil fuels [1]. Due to her geographical location (lying between 4 ° and 14 ° north of the equator), Nigeria is blessed with a significant level of solar insolation. The country receives about 5.08 x 10^{12} kWh of energy per day from the sun, and if solar appliances with 5% efficiency are used to cover 10% of the country's surface area, then 2.54 x 10^{6}MWh of electrical energy, from solar energy resource, which is equivalent to 4.656 million barrels of oil per day will be realisable [2]. There are between 2000 – 3000 hours of sunshine per year in Nigeria translating to between 3.5 – 7 kW/m^2/day of energy being received from the coastal latitude to the far North [3]. The use of firewood requires constant attendance to the fire and stirring of the food to prevent burning. The pot is covered by soot on the outside and food sticks to the bottom inside, wasting food and causing extra work to clean. There are dangers of wind spreading big fires and small children falling into open fires. Smoke from the fire causes lung and eye diseases. The cost of replacing cut trees is the market price of cut wood the proceeds of which are never used to replace the cut trees. A judicious use of solar energy by means of solar cooking can cut down the cooking fuel expense by more than 60% and can help to overcome the harmful effects arising from the combustion of current "dirty" cooking fuels. A number of solar cookers have been designed and developed by many authors like the development, evaluation and parametric modelling of box-type solar cooker [4], the development of a solar device for crop drying and cooking [5], design, development and testing of a double reflector hot box solar cooker with a transparent insulation material [6]. In general view, this project design and evaluation of a solar cooker for an indoor use allows solar cooker to be used right inside the house just the way an oven system works. Several projects on solar cooker has been done but mostly used outside but this allow for efficient use of solar energy for household cooking.

II. MATERIALS AND METHODS

The testing of the designed solar cooker was carried out in an open-close environment that allowed the inner section for indoor part and outer section for solar energy trapping. The cooker was then positioned well to maximum possible solar radiation at a particular time is focused. The materials and equipment used for the testing include: Stop watch, Data Logger (REED SD-947, model:H264995), Solar-Meter (Dr Meter, model: SM206), digital thermometer, K type thermocouple wires, weighing balance, measuring beaker and cooking equipment (Pot, clean cloth, foam, kegand eating utensils). Figure 1 shows the isometric view of the box type integrated solar cooker while the bill of engineering measurements and evaluation is presented in Table 1.

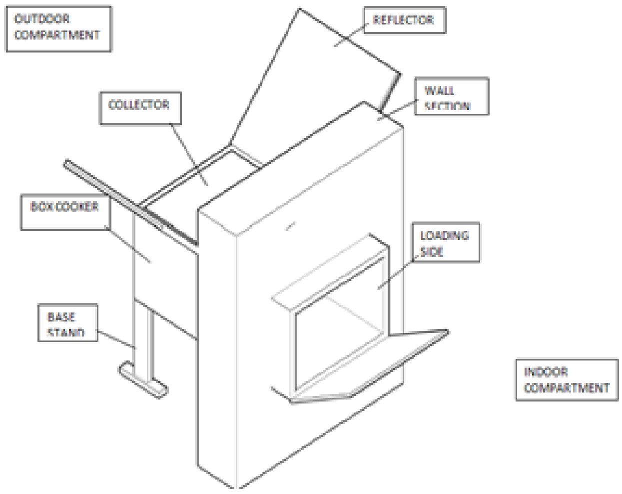

Figure 1: Isometric Drawing of the Solar Cooker

Table 1: Bill of Engineering Measurement and Evaluations for a building-integrated Box Type Solar Cooker

S/N	COMPONENT	DIMENSION	MATERIAL
1.0	Outdoor Section	100 mm x 20 mm x 550 mm	20 mm thick Teak wood
2.0	outdoor inner	170 mm x 130 mm x 450 mm	3 mm plywood
3.0	indoor section	550 mm x 550 x 350 mm	20 mm thick Teak wood
4.0	Insulator (lagging)	100 mm x 550 x 550mm	corn husk
5.0	Double glazing	50 mm x 550 mm x 550 mm	3 mm tempered float glass
6.0	3 planes reflectors	540 mm x 550 mm x 15 mm	Aluminium foil placed atinclined angle 35° on the plywood
7.0	Wall section	1000 mm x 850 mm x 200 mm	Teak wood and plywood
8.0	Absorber Plate	280 mm x 300 mm x 355 mm	1.4 gauge mild steel sheet painted matt black
9.0	cooking pot	210 mm diameter & 90 mm height	Aluminium
10.0	standing leg	560 mm x 70 mm & 200 mm x 40mm	Melina wood of 20 mm thickness
11.0	base sitter	350 mm x 660 mm	25 mm thick Omo wood
12.0	indoor section door	282 mm x 355 mm x 350 mm	trapezoidal door of 20mm Thickness.

A. *Performance Evaluation of the Solar Cooker*

i. **Capacity of the Cooker:** The capacity is also referred to as the power of the cooker [7]. This was obtained using Equation 1

$$P = \frac{MwxCwx\Delta Tw}{\Delta t} \qquad (1)$$

Where: P is the Power (Watts), Cw is the Specific heat capacity of water (4200 J/kg.K), ΔTw is the change in temperature (that is, $(T_2 - T_1)$ = Rise in temperature of water {K},T_1 is the Initial temperature of water (T_1 = 30°C + 273 = 303 K), T_2 is the Final temperature of water (T_2 = 100oC + 273 = 373 K), Δt is the Time required to boil the water at 100°C, sec. (Given that it takes the cooker 5 minutes to boil 1.5 kg of water,Then, Mw = 1.5; δt = 300 seconds).

Total Surface Area of the Collector and reflector of the cooker was obtained using Equation 2 [8].

$$P = HavxAx \in \qquad (2)$$

Where: Hav is the Average solar insolation (700 W/m^2),A is the Total surface area of the concentrator (m^2), € is the Emissivity of the reflecting material (0.95), P is the Power of the solar cooker (1,470 Watts).

$$\text{Thus, } A = \frac{P}{Havx\in} \qquad (3)$$

The heat gain by water was obtained using Equation 4

$$Qw = Mw \times Cw \times \Delta Tw \qquad (4)$$

Where: Mw is the Mass of water (1.5 kg), Cw is the Specific heat capacity of water (4200 J/kg.K), ΔTw is the Temperature rise of water, $T_2 - T_1$

The sensible thermal efficiency of the cooker was obtained using Equation 5 [9].

$$\eta = \frac{P}{\delta t \text{ x Ac x Hav}} x\ 100 \qquad (5)$$

Where: η is the Thermal efficiency, P is the Cooking power of solar cooker (1470 Watts), Ac is the Area of concentrator (2.2 m^2), Δt is the Time taking for water to rise to desired (final) temperature (5 mins), Hav is the Average solar insolation (700 W/m^2).

The cooking power prediction model was validated by comparing observation from tests of the box cooker with model performance predictions to determine fitness.

$$P = \frac{(Tf-Ti)\ MCw}{600} \qquad (6)[10: ASAE, 2002]$$

$$Ps = \frac{Pi700}{Ii} \qquad (7)\ [10: ASAE, 2002]$$

Where: P is the cooking Power (watts), T_f is the final water temperature (°C), T_i is the Initial water temperature (°C), M is the mass of water (Kg), C_w is the Heat capacity of water (4186 Jkg-1K-1), Ps is the standardized cooking power (W), Pi is the interval cooking power (W), I is the interval insolation (Wm-^{2})

ii. Stagnation Test: this is a condition in which useful energy that is available inside the solar cooker is not being used. Cooker was emptied and no cooking took place doing this period of evaluation. The test was carried out to determine the maximum possible temperature the solar cooker can attain at any particular time [11]. Stagnation test was carried out as setup on the plate, the solar cooker reflectors were set at an angle close enough to reflect the trapped energy to the collector. The collector surface of the glass was cleaned with a neat foam. Two thermocouples were placed inside the cooker one to measure the air temperature inside the cooker at various temperature while the other thermocouple wire was placed on the absorber surface of the cooker. The readings were logged into the data logger for a long period. The solar meter was then placed in position beside the collector and tilted to focus the solar radiation. K type thermocouple was also used to measure the ambient temperature. The box reflectance lid was aligned perpendicularly to the solar radiation but stationary throughout the experiment because it is meant to be incorporated to conventional kitchen.

iii. **Boiling Test:** This test was carried out to determine the thermal efficiency of the solar cooker in boiling of water. This is to determine the time taken for the solar cooker to heat a known quantity of water. The set-up for the experiment was done with a hole made on the cover of the pot lid and thermocouple wire was placed inside it to the level of the water but care was taken not to touch the pot base. The port head of the run wire was placed at a port on the data logger to record and store the readings at five (5) seconds interval. Another thermocouple wire was run from the absorber plate to the data logger for temperature reading on the absorber plate and was also recorded. The last thermocouple wire was the one that was placed on the collector surface which helps to collect the ambient temperature reading of the solar cooker environment.

iv. **Controlled Cooking Test:** The food and quantity of water was measured before controlled cooking test is carried out. The mixture of known food and water is then introduced to the pot and placed into the cooker. The solar cooker was pre-heated before the pot is introduced into the cooker. The time that it took to cook was then recorded. The thermocouple wire run from the pot and the absorber plate to the data logger until the food was done for temperature reading taken to cook the food and the time taken recorded with the use of stop watch.

v. Determination of Figures of Merit: 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 can be determined [12]. 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 8:

$$F_1 = \frac{Tps - Tas}{Gs} \quad (8)$$

Where: F_1 is the first figure of merit, Tps is the stagnation temperature (°C), Tas is the ambient temperature (°C), Gs is the solar insolation at stagnation (W/m^2),

The second figure of merit was obtained from the water boiling test and calculated from Equation 9:

$$F_2 = \frac{F1\,(Mc)w}{A\,(t2-t1)} \, loge \left[\frac{1-\frac{Tw1-Ta}{F1G}}{1-\frac{Tw2-Ta}{F1G}}\right] \quad (9)$$

Where: F_2 is the second figure of merit, M is the mass of water (kg), C is the specific capacity of water (J/kg°C), t_2 - t_1 is the time taken for water to boil from Tw_1 to Tw_2 (secs), Ta is the average ambient temperature over time period t_2 - t_1 (°C), G is the average solar radiation over a time period t_2 - t_1 (W/m^2), Tw_1 is the temperature of water at time t_1 (°C), Tw_2 is the temperature of water at time t_2 (°C).

III. RESULTS

An integrated solar box cooker was designed, constructed and evaluated. The figures of merit obtained are presented in Table 2 while the stagnation temperature results if presented in Figures 2-6 and the results of water boiling test obtained by boiling one liter of water using the solar cooker is presented in Figures 7 - 11

Table 2: Figures of Merit

Parameter	Gs(W/m^2)	T_{ap}(°C)	F_1	F_2	T_{ia} (°C)	T_{amb} (°C)
Day1	890	96.6	0.09	0.20	85.5	36.2
Day2	954	113.8	0.12	0.24	105.4	32.5
Day3	677	101.9	0.13	0.26	71.3	38.7
Day4	854	103.9	0.11	0.23	97.4	41.1
Day5	1032	129.3	0.12	0.25	98.2	45.7

Where: T_{ap} and T_{ia} is the absorber plate and inner air temperature of the cooker respectively, T_{amb} is the ambient temperatures, F_1 and F_2 is the first and second figures of merit respectively.

A. Controlled Cooking Test

Tables 3 and 4 shows the different time the solar cooker cooked different food items. It was noted that during the time of experiment, the solar insolation was not stable. This really affected the cooking time of the food items.

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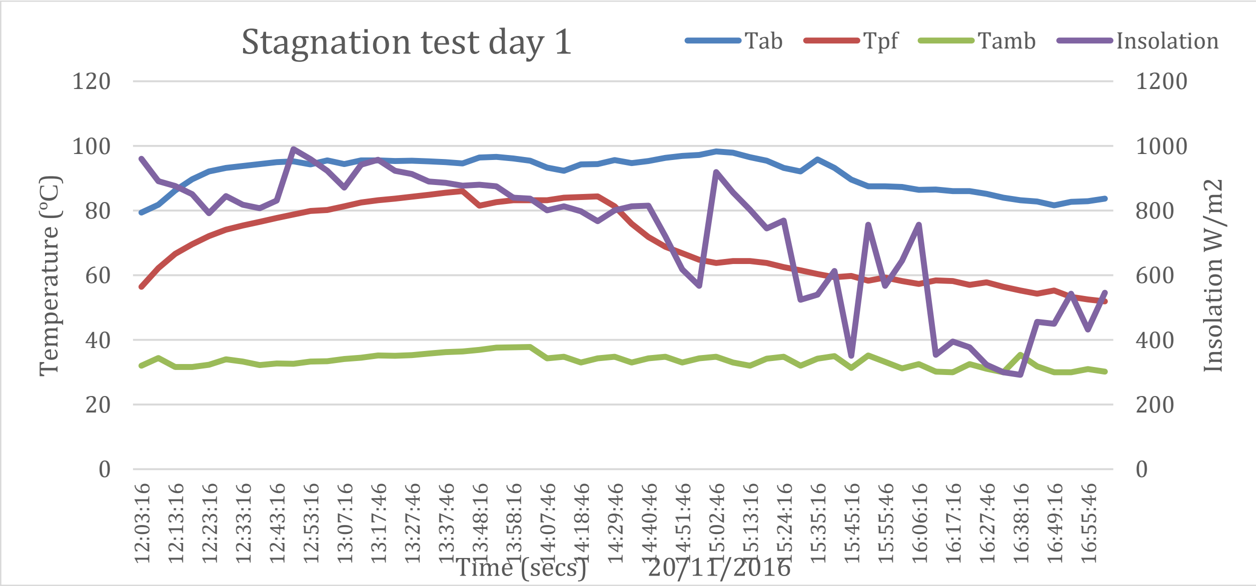

Figure 2: Stagnation Temperature at Day 1

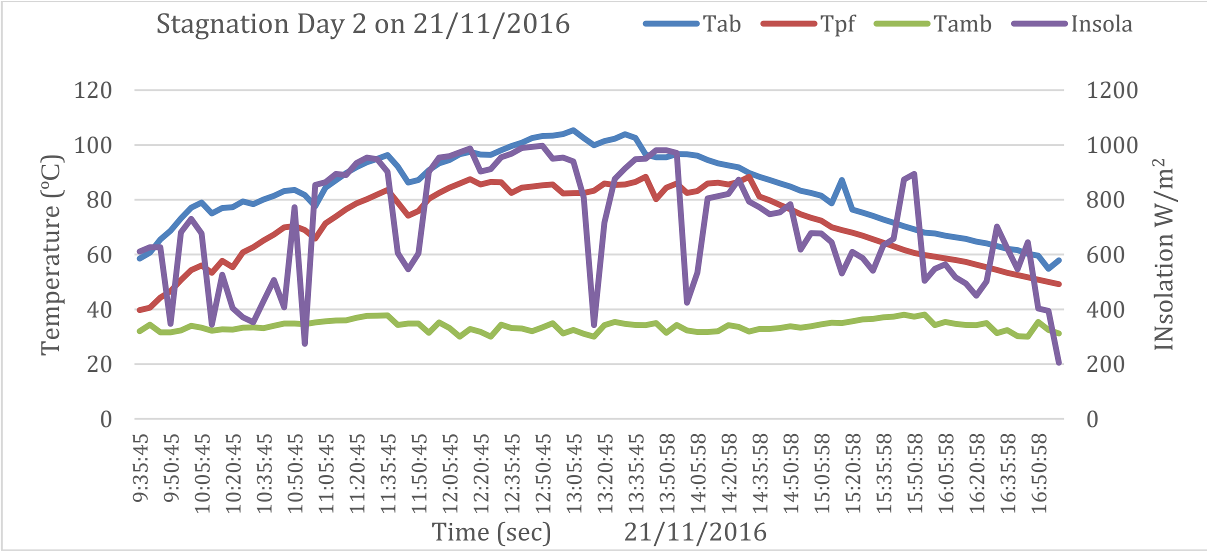

Figure 3: Stagnation Temperature at Day 2

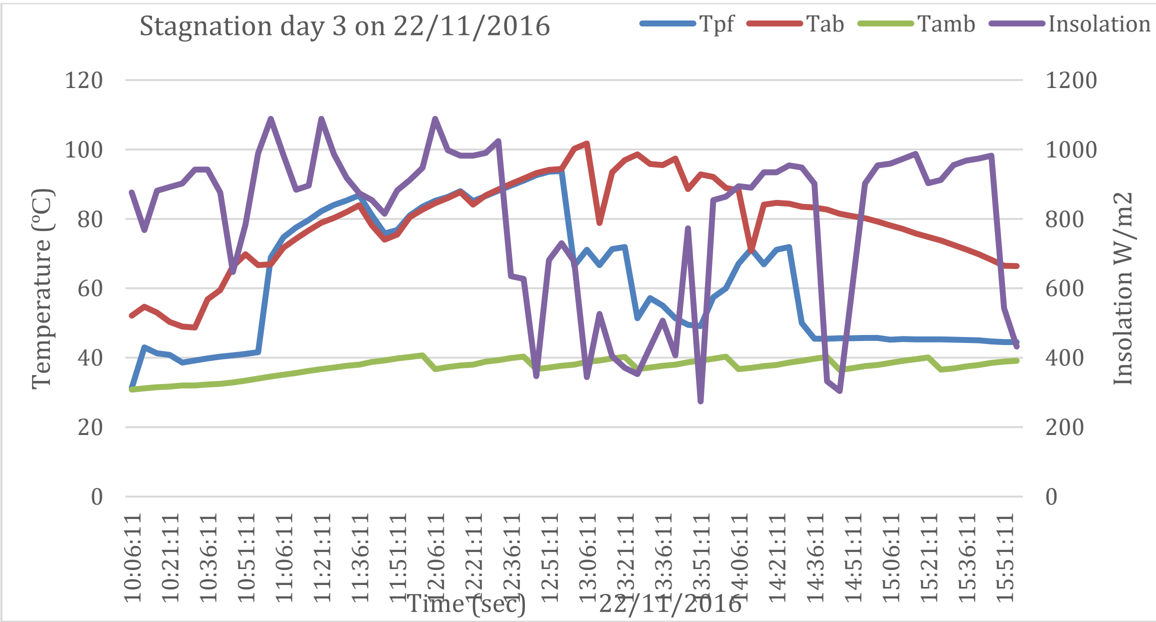

Figure 4: Stagnation Temperature at Day 3

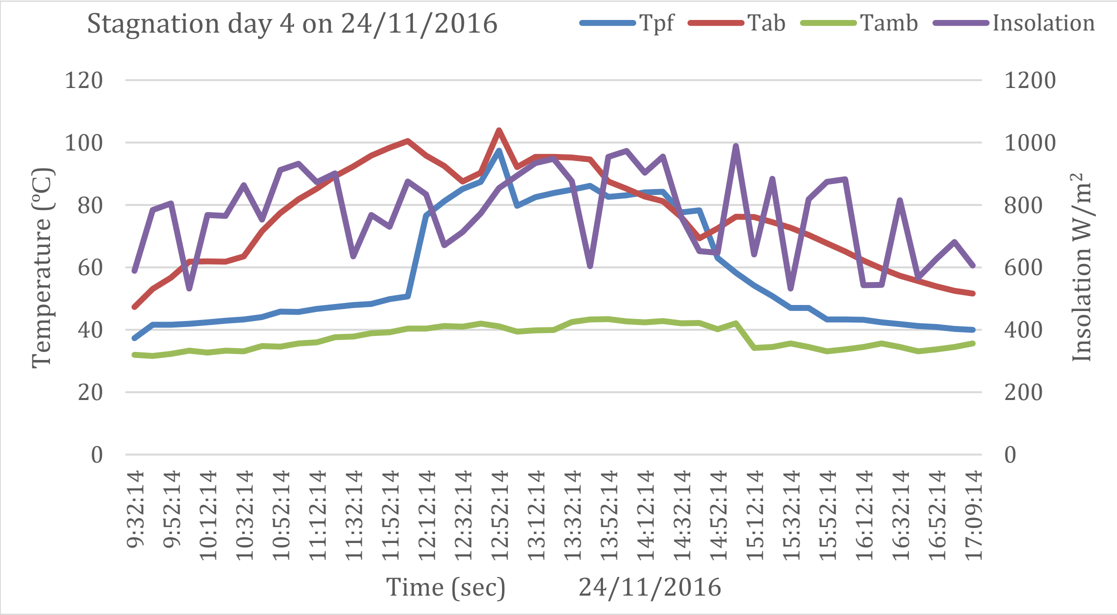

Figure 5: Stagnation Temperature at Day 4

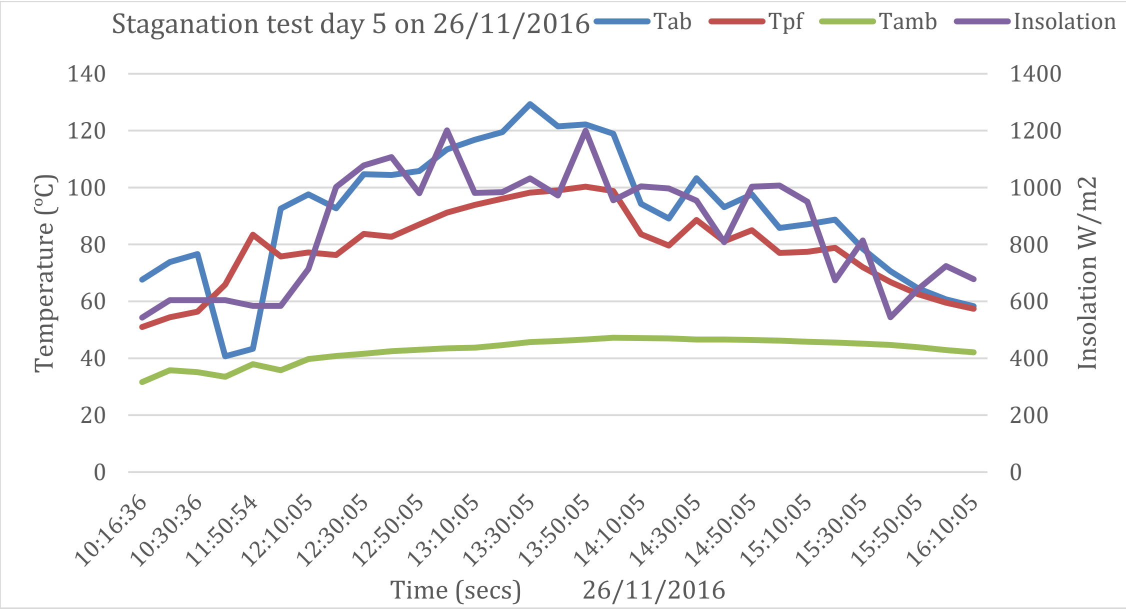

Figure 6: Stagnation Temperature at Day 5

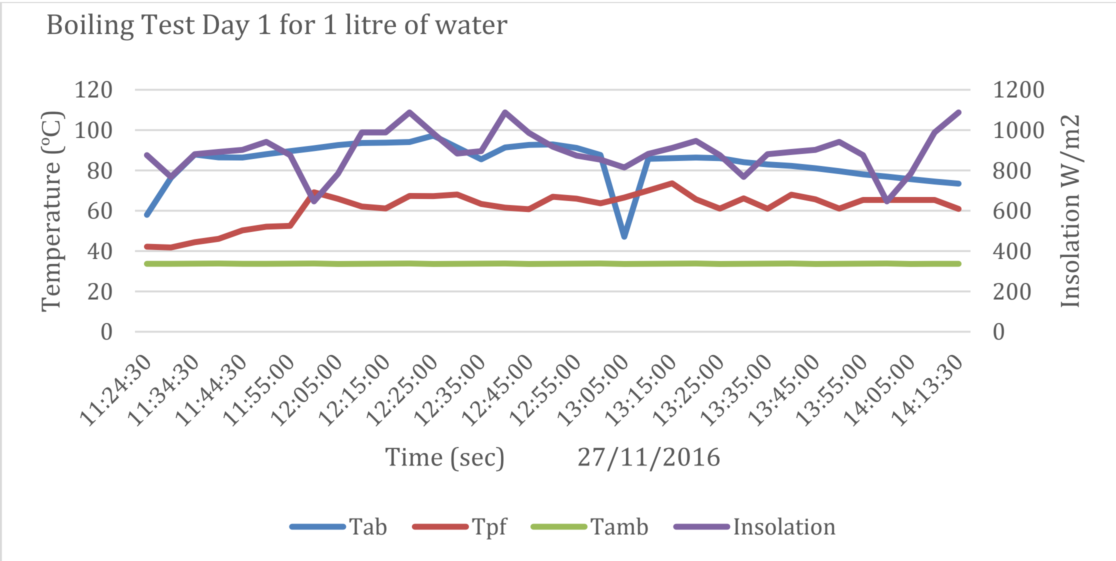

Figure 7: Boiling Test at Day 1

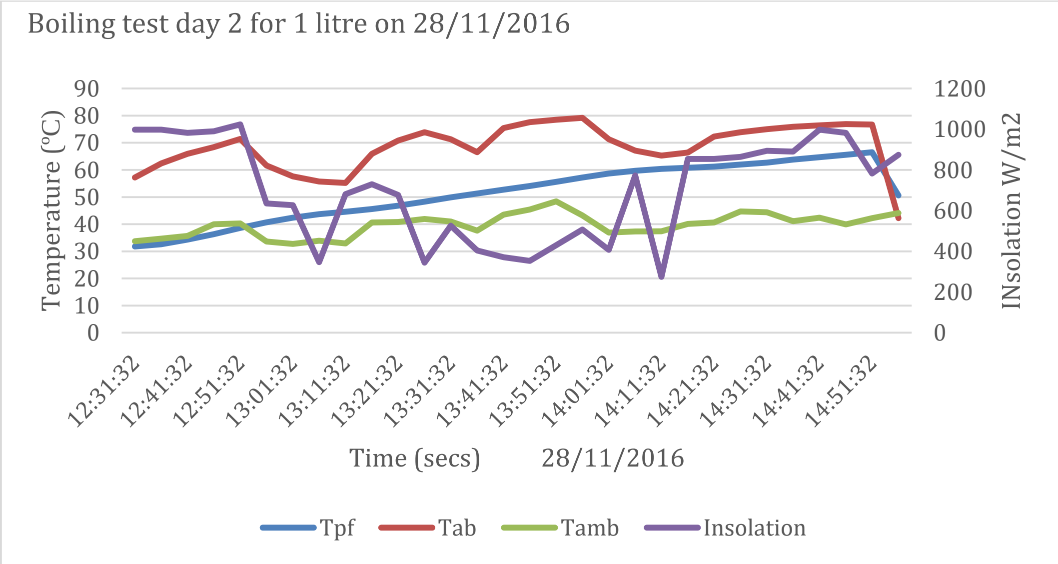

Figure 8: Boiling Test at Day 2

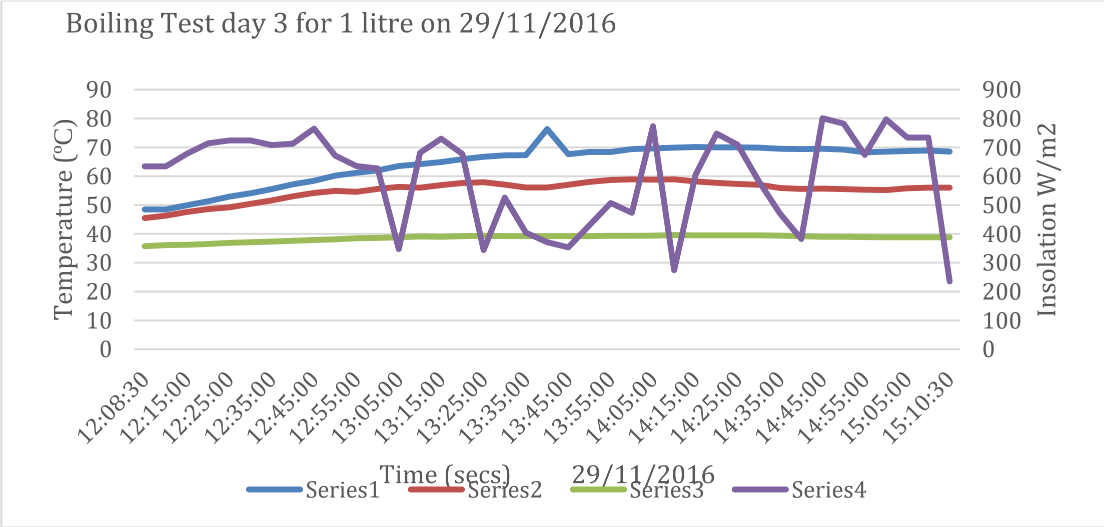

Figure 9: Boiling Test at Day 3

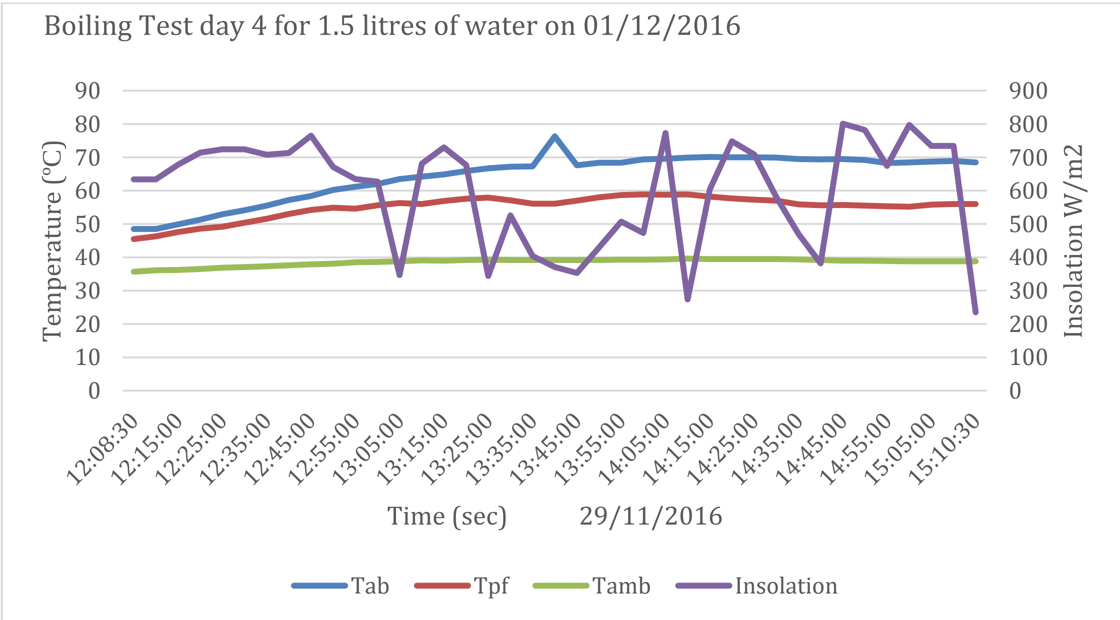

Figure 10: Boiling Test at Day 4

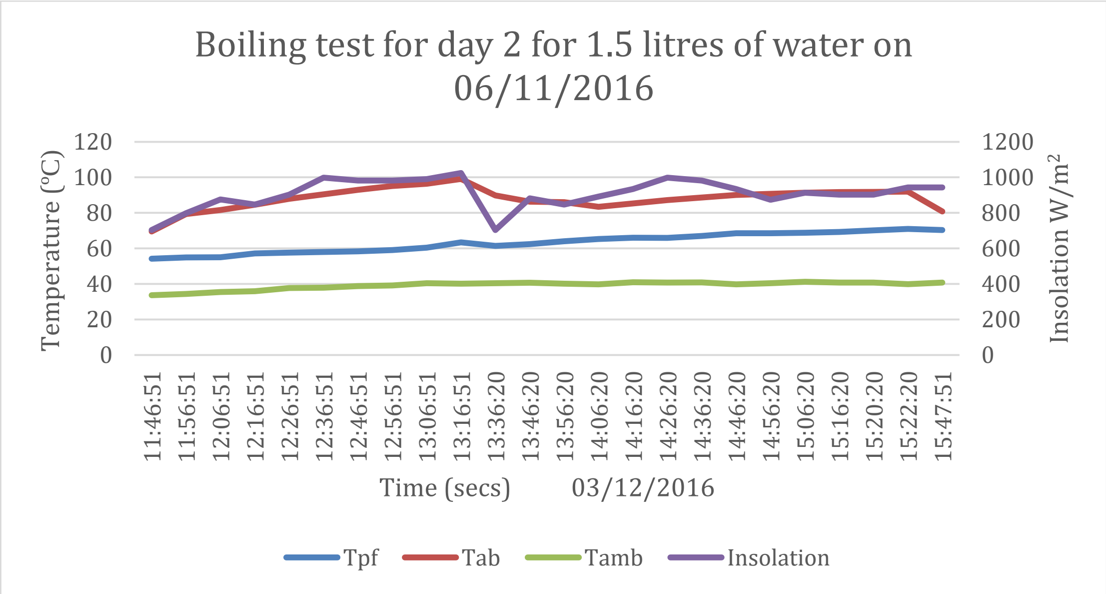

Figure 11: Boiling Test at Day 5

Table 3: Controlled cooking test Result

Type of food	Weight (g)	Time taken (minutes)	Remarks
Indomie noodles	200	105	The Experiment commenced at 1:00 with an average solar intensity of 871 W/m^2 Date: 05/12/2016
Water	205.8	60	
Egg	2 pieces	95	

Table 4: Cooking Test Result

Type of food	Weight (g)	Time taken (minutes)	Remarks
Rice	300	180	The experiment commenced at 12 noon when the solar intensity was 912 W/m^2 Date: 06/12/2016
Water	375	55	
Egg	2 pieces	100	

B. *DISCUSSION*

The stagnation temperatures reached by the cooker was fluctuating as a result of variations in the solar intensity. Stagnation test recorded has an average insolation of 733.6W/m^2 with stagnation temperature of the absorber plate ranging from 72.31 – 95.12℃ and ambient temperature ranges from 33.4 – 43.89℃ and pot temperature was 69.14 – 82.7℃. Similar findings were reported by [13] who obtained an average insolation reading of 716.74, 895.89, 946.12, and 1075 W/m^2 at temperature of absorber plate ranging from 108 - 124℃, temperature of air in pot to be 50 - 92℃ while the ambient temperature was 32 - 37 ℃. Also, [14] reported an average insolation reading of 720 – 780 W/m^2 with pot temperature of 103.4℃ and average absorber temperature reading of 106.6℃.

The boiling test was carried out by boiling of 1 litre of water and 1.5 litres. The average temperature range for boiling 1 and 1.5 litre of water was 60.3$\pm$ 30 and 52.3$\pm$ 25 respectively. An average of 90 mins was used to boil 1 lit of water, this time is far higher than value reported by [4] and [13] in their study on comparative analysis of a foiled interior and black interior box-type solar cookers and potential use of box-type solar cooker in developing countries respectively reported that 1 lit of water boiled at 50 and 57 minutes respectively. The comparative difference may be to the fluctuation in insolation and heat losses from the openings of the oven solar cooker. However, [14] on investigating the suitability of different heat storage media in double exposure box-type solar cookers reported similar findings for boiling 1 lit of water at 90 minutes time interval

Controlled cooking test was carried out with the cooking of indomie noodles and jollof rice. It took 105 minutes to cook 200 grams of indomie noodles while jollof rice cooked at 180 minutes. Previous research by [4] reported that rice of 400 grams cooked at 80 minutes. Also, [14] reported similar cooking time of 34 minutes for 70 grams of indomie noodles.

IV. CONCLUSION

The indoor solar cooker was designed and constructed. It was then experimentally tested and the performance of the indoor solar cooker was also evaluated in terms of stagnation, water boiling and control cooking test. The constructed solar cooker satisfactorily boiled 1 litre and 1.5 litres of water. Also, the solar cookers for an indoor use was used to cook indomie noodles, rice and eggs. The use of solar energy in cooking is expected to protect environment and reduce health risks. Therefore, the design and experimental testing of a building integrated box type solar cooker should be adopted.

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