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Development of a Building Integrated Hybrid Solar Cooker

*A. K. Aremu[a], O. A. Adefehinti[a], T. O. Ajao[a]**

[abc] Department of Agricultural and Environmental Engineering, Faculty of Technology, University of Ibadan, Ibadan, Oyo State, Nigeria

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ABSTRACT

Solar cooker is important in presenting an alternative energy source for cooking but the major drawback is the time spent outside to monitor the food during the cooking process, because most solar cookers are designed for external use. This study aims to reduce the cost of purchasing fuels, drastic reduction in the carbon emission to enhance cleaner and safer environment for healthy living and the materials of construction are readily available hence the need to develop an affordable building integrated hybrid solar cooker. The test carried out included the stagnation and water heating test, then the figures of merit were determined. Controlled cooking test was done by cooking five pieces of egg for 90 minutes, and the cooking of 820 g of rice at 120 minutes. The maximum stagnation temperature for evaluation reached by the absorber plate of the indoor box cooker is 158°C while the corresponding maximum pot temperature is 167.4. The maximum temperature attained by heating 1kg of water is 105.3, the maximum temperature attained by heating 1.5 kg of water is 101.6 and the maximum temperature attained by heating 2kg of water is 100.4. The maximum standardized cooking power attained during evaluation was 392W. The first figure of merit at stagnation temperature for six days was 0.17, 0.18, 0.10, 0.081, 0.091 and 0.094 respectively and the second figure of merit at water temperature for six days was 0.44. 0.50, 0.35, 0.21, 0.28 and 0.37 respectively.

1. Introduction

Energy is vital provided adequate food supplies are to be converted into suitable diets. Solar cooking offers an effective method of utilizing solar energy for meeting a considerable demand for cooking and, hence, protecting the environment [1]. The technology of solar heating involves the conversion of solar energy to heat energy. Solar heating systems could be box-type, concentrating type or a hybrid of the two. Box type solar cooker makes use of both diffuse and direct radiation while the concentrating type depends on its ability to make use of direct radiation only [2].

Some of the reported works on modelling of solar device include mathematical model for a box-type solar cooker, accounting for the solar energy input and internal heat exchange within the pot, walls and top cover [3]. Considerable efforts have been put into the development and performance testing of varieties of solar cookers and their suitability for cooking different foods. A thermal model for solar box cookers loaded with one, two or four pots was developed. It is clean, renewable, abundant and available in the tropical region of the world [4]. The consequence of its increased utilization would yield an all-round benefit, both in terms of cleaner environment and monetary gain, for individual users, as well as the nation [5].

A standard box solar cooker possesses a guiding principle which is to concentrate heat while letting pass the sunlight through a pane in a closed well-insulated box. The light is captured in the box and is transformed into heat when it is absorbed by the pot while concentrated solar cookers work on the principles of concentrating the direct solar rays to raise water or food temperatures to cooking level. Cooking temperatures begin at about 65^0C, although temperatures of 120 to 200^0C are preferred [6].

Several designs of the solar cookers have been studied in order to optimize their performance. These designs vary by their geometrical form and geographical location [7]. It was reported that an effective solar cooker generally forms part of two categories such as the box-type and parabolic focusing type [6]. The open reflector type solar cookers focus the sun's ray on open cooking pots while solar oven traps the sun's heat inside the insulated boxes with transparent lids. Most solar ovens are variations of bread box type developed by two Arizona women, Barbara Ker and Sherry Cole [8].

The standard of living in developing countries is so expensive, as a result of this the masses are compelled to make use of firewood or charcoal for cooking purposes which is not healthy for them because of the carbon emission associated with it [9]. The use of solar cooker would cause a reduction in the cost of purchasing gas and kerosene to the barest minimum [10], preserve more of the natural nutrients of food by cooking at lower temperatures [11], hence, there is the need to develop an integrated solar cooker which is cheap, readily available for domestic cooking purposes in a tropical environment. This study, therefore, aimed at designing and constructing an integrated hybrid solar cooker.

2. Methodology

2. 1 Materials

The construction of work was done with the selection of some readily available materials in the market. Below are the lists of the material used in the construction of a hybrid solar cooker:

a. 2mm Aluminum plate
b. Aluminum angle iron
c. Rivet pin
d. Cork board
e. Matt black paint
f. Aluminum foil
g. 0.3mm Aluminum sheet
h. Square pipe
i. 4mm Perspex
j. Television satellite dish used as a parabolic concentrator

The box cooker was covered with a transparent perspex to enable the collection of sunlight in to the cooker cavity from the top while the parabolic concentrator was placed at the side to focus trapped sunlight to the direction of the box cooker to increase the amount of heat trapped in the box cooker. The equipment used during the construction of the hybrid solar cooker included the following:

a. Multichannel data logger (REED SD-947)
b. Solar meter (Dr Meter, SM 206)
c. Stop watch
d. K-type thermocouple wire
e. Measuring beaker

f. Anemometer (AM-4812)
g. Weighing scale (Camry EK 5350)
h. Cooking equipment

2.2. Method

Evaluation of the performance of the solar cooker

The standard testing method as stated in ASAE standard requires a water heating test which was carried out [12]. The solar cooker was evaluated based on the following parameters;

i. Capacity of the cooker

The capacity is also referred to as the power of the cooker. This was obtained using Equation (1) [9] as follows:

$$P = \frac{M_{w \times} c_{w \times} T_w}{\Delta t} \quad (1)$$

Where;

P is the Power (Watts),
Cw is the Specific heat capacity of water (4200 J/kg.K),
ΔT_W is the change in temperature ($T_2 - T_1$) = Rise in temperature of water, (°C),
T_1 is the Initial temperature of water
T_2 is the Final temperature of water
Δt is the Time required to boil the water in seconds
M_W is the mass of water.

ii. Standardized Cooking Power

The cooking power for each interval was corrected to a standard insolation of 700W/ m^2 using the Equation (2) below:

$$P_s = P\frac{(700)}{(I)} \quad (2)$$

Where;

P_s is standardized cooking power

iii. Temperature Difference

The ambient temperature for each interval was subtracted from the average cooking vessel contents temperature for each corresponding interval given by Equation 3;

$$T_d = T_w - T_a \quad (3)$$

iv. Stagnation Test

This was used to determine the thermal performance of the hybrid solar cooker. The cooker was operated without cooking (under no load) to determine the maximum possible temperature attainable at a particular point in time. The hybrid solar cooker was placed in an open environment facing the direction of the sun. Thermocouples was used to obtain the maximum temperature of the absorber plate, internal air and the ambient temperature. These readings were recorded at every 5 seconds intervals. This test was repeated and carried out on six different days.

v. Water Heating Test

This was carried out to determine the time it takes the hybrid solar cooker to boil a known volume of water. 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. The readings were taken at 5 seconds interval and was concluded when the water reaches boiling point, water temperature, absorber plate temperature, ambient temperature and boiling time were all measured using stop watch and thermocouple for six different days which is a method that have been previously used by several researchers [13, 14].

vi. 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 can be determined [15]. 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 4**:**

$$F_1 = \frac{T_{ps} - T_{as}}{G_s} \tag{4}$$

Where;

F_1 is the first figure of merit
T_{ps} is the stagnation temperature (°C)
T_{as} is the ambient temperature (°C)
G_s is the solar insolation at stagnation (W/m^2)

The second figure of merit was obtained from the water boiling test using Equation 3 [16].

$$F_2 = \frac{F_1 (M_C)w}{A(t_2 - t_1)} log\ e \left[\frac{1 - \frac{T_{w1} - T_{as}}{F_{1G}}}{1 - \frac{T_{w2} - T_{as}}{F_{1G}}}\right] \tag{5}$$

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 T_{W1} to T_{W2} (secs)
T_a 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)
T_{W1} is the temperature of water at time t_1 (°C)
T_{W2} is the temperature of water at time t_2 (°C)

3. Results and Discussion

Table 1: Components of a hybrid solar cooker

S/N	Component	Dimension	Material1
1	Outdoor box	440 mm x 440 mm x 200 mm	2 mm Aluminum plate
2	Inner box	180 mm x 360 mm x 180 mm	2 mm Aluminum plate
3	Angle iron	1000 mm length	Aluminum angle iron
4	Insulator	180 mm x 360 mm x 180 mm	Corkboard
5	Glazing	440 mm x 440 mm and 440m x 200 mm	4 mm Perspex
6	Parabolic dish	1050 mm length x 940 diameter x 100 mm depth	Satellite dish and foil
7	Kitchen wall	1110 mm x 610 mm x 260 mm	Plywood and teak
8	Indoor gate cover	410 mm x 150 mm	2 mm Aluminum plate
9	Base sitter	400 mm x 400 mm x 700 mm	2 mm Aluminum plate
10	Parabolic stand	810 mm	Mild steel square pipe
11	Cooking pot	240mm diameter and 65mm height	0.5 mm Aluminum sheet
12	Indoor gate	300 mm x 100 mm	Rectangle door of 2 mm

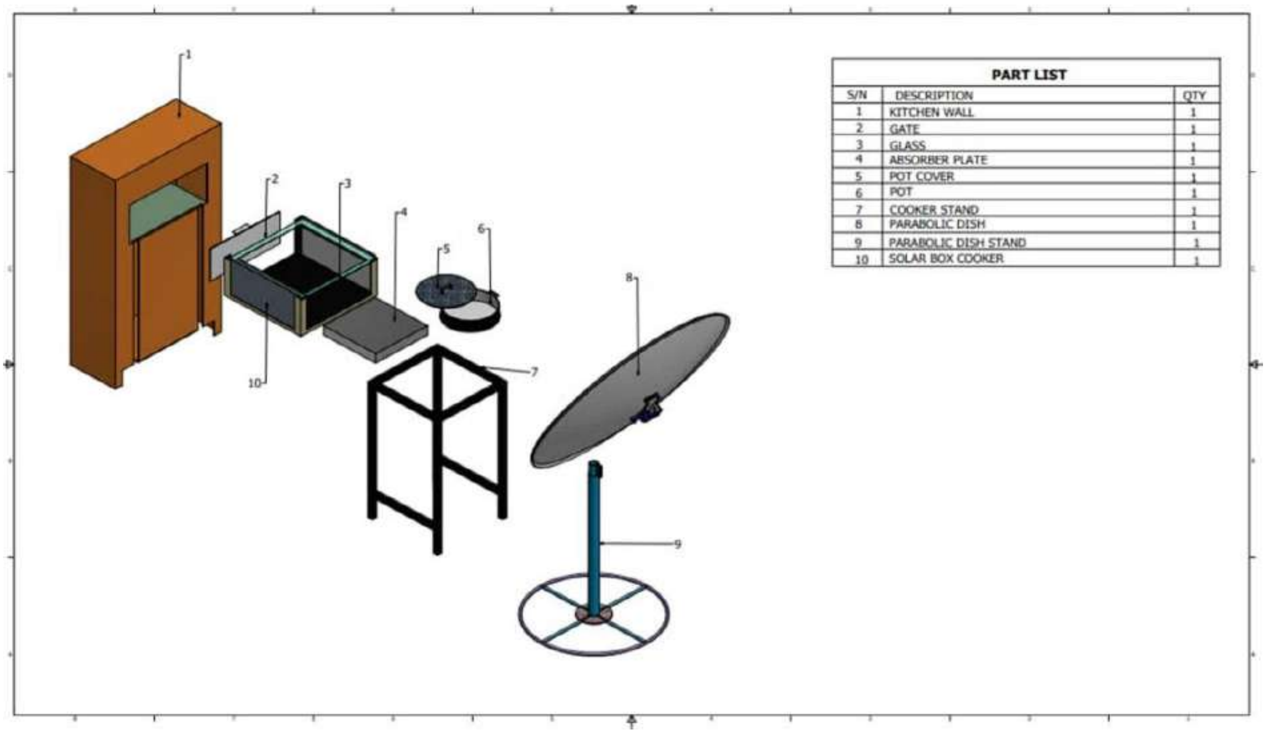

Figure 1: Exploded view of a Hybrid Solar Cooker

Table 2: Summary of solar cooker's performance at stagnation

Day	Insolation (w/m^2	T_{abs}	T_{pt}	T_{amb}	Wind speed(m/s)
8.10.21	374	98.1	101.2	37.2	0.5
9.10.21	415	108.2	119.1	43.5	0.1
11.10.21	1338	133.5	142.1	34.7	0.3
30.11.21	1345	141	146.4	35	0.4
1.12.21	1371	146.8	155.3	36.4	0.0
2.12.21	1406	158	167.4	35.1	0.1

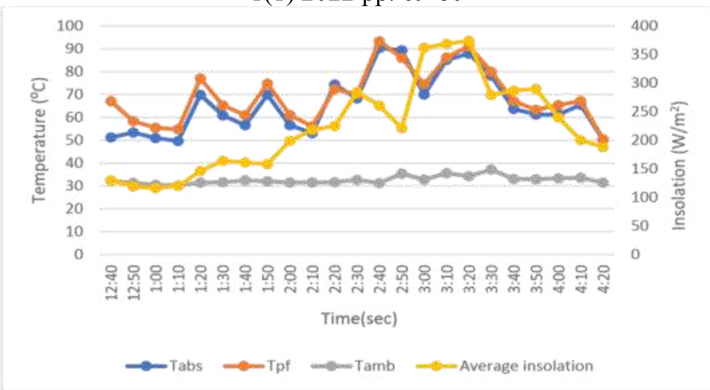

Figure 2: Stagnation Test (Day 1)

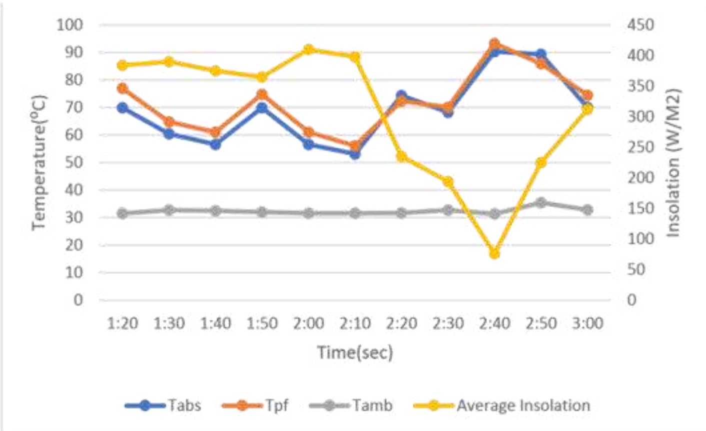

Figure 3: Stagnation Test (Day 2)

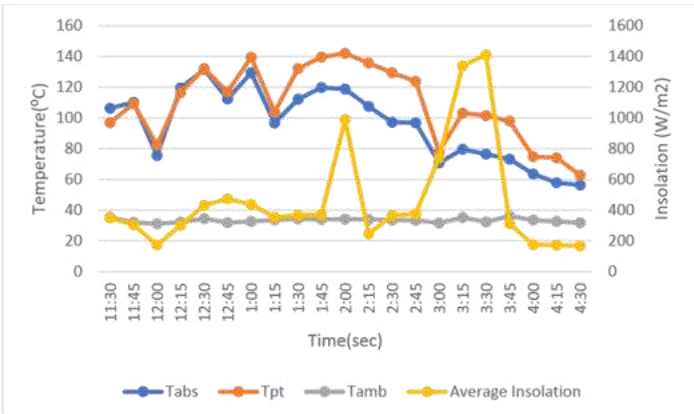

Figure 4: Stagnation Test (Day 3)

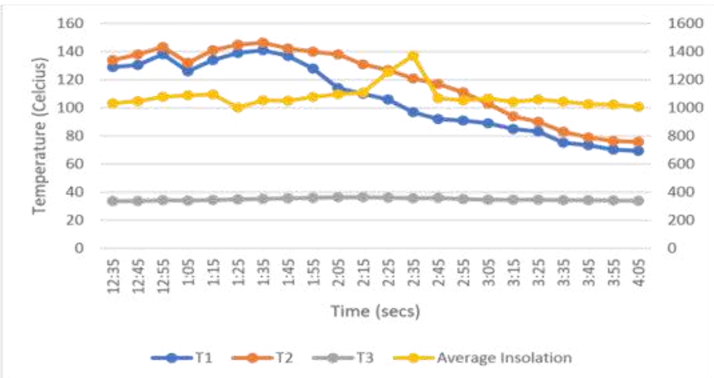

Figure 5: Stagnation Test (Day 4)

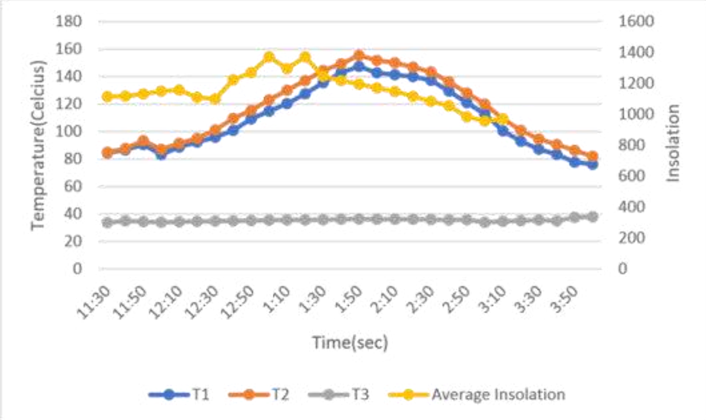

Figure 6: Stagnation Test (Day 5)

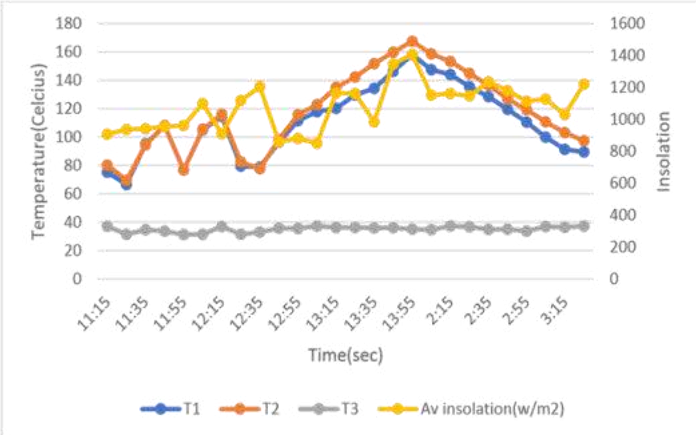

Figure 7: Stagnation Test (Day 6)

Table 3: Summary of solar cooker's performance in heating water

Day	Insolation (w/m^2	M_w	T_{abs}	T_{pt}	T_{amb}	Wind speed(m/s)
15.10.21	847	1.0	72.8	72.4	37.5	0.0
18.10.21	730	1.5	73.6	70.2	35.5	0.4
21.10.21	812	2.0	68.3	63	36.4	0.0
3.12.21	1250	1.0	123.1	105.3	34.8	0.2
4.12.21	1118	1.5	89.3	101.6	39.5	0.0
5.12.21	1100	2.0	87.2	100.4	36.3	0.7

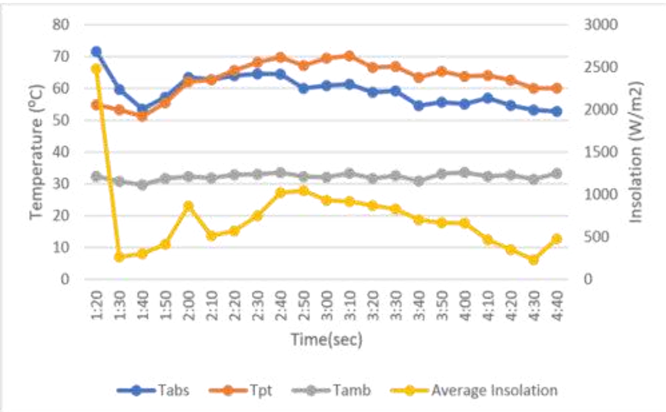

Figure 8: Water Heating Test (Day 1)

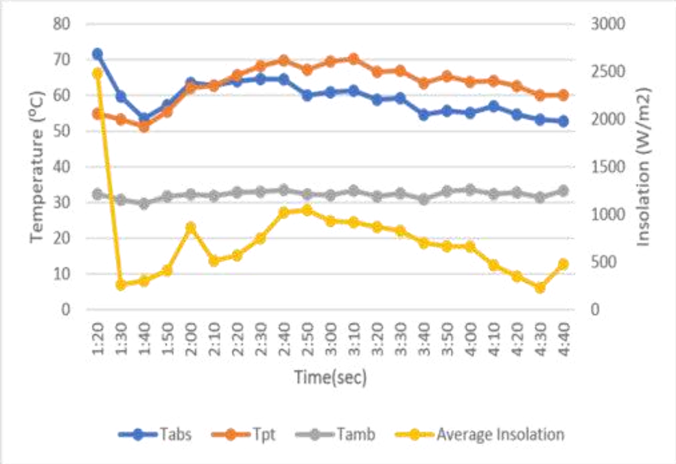

Figure 9: Water Heating Test (Day 2)

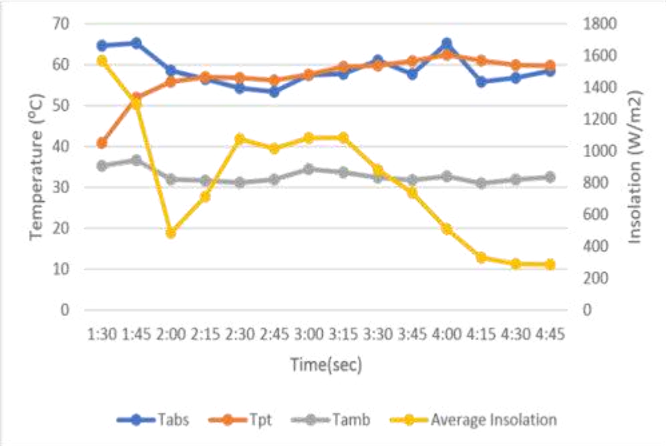

Figure 10: Water Heating Test (Day 3)

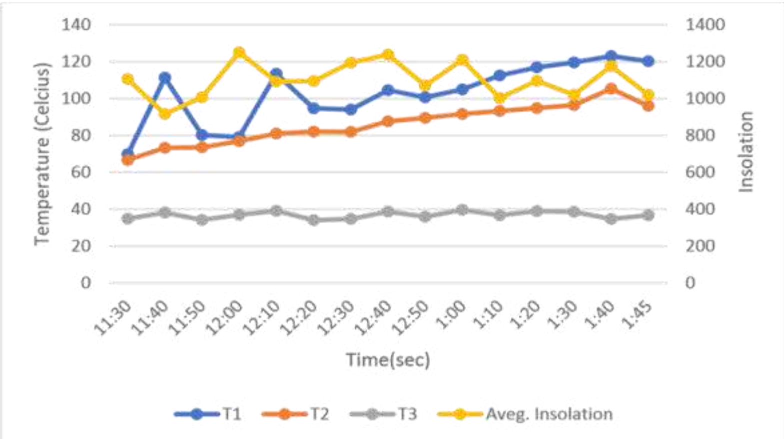

Figure 11: Water Test (Day 4)

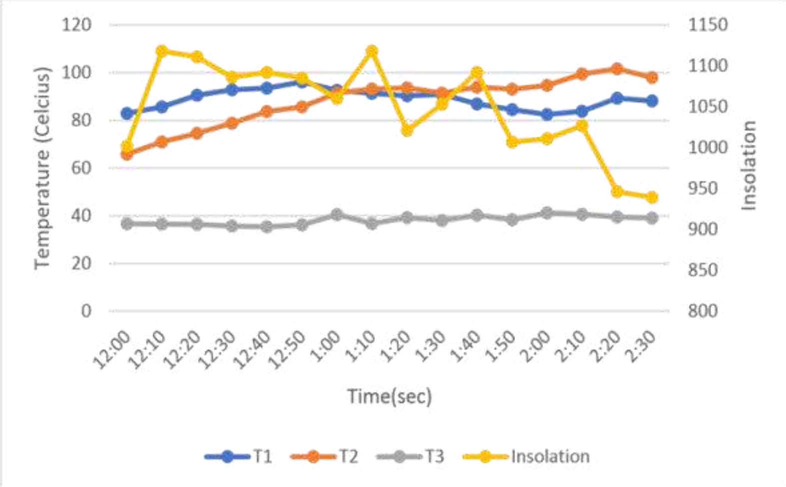

Figure 12: Water Heating Test (Day 5)

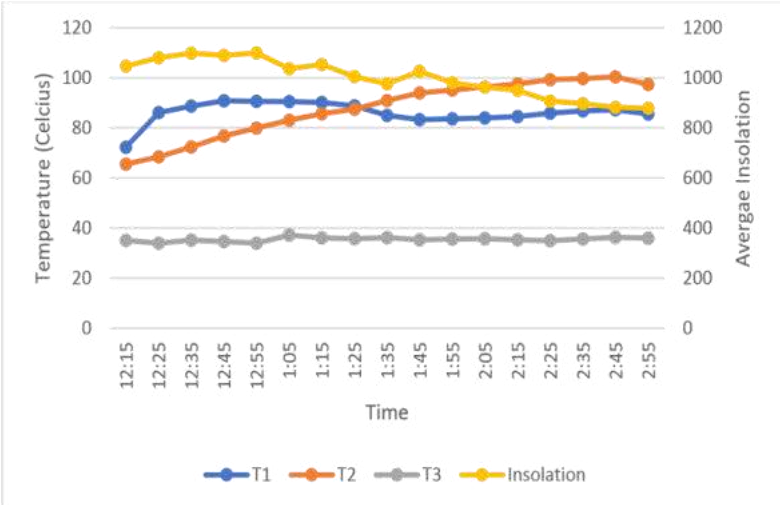

Figure 13: Water Heating Test (Day 6)

Cooking Test

Table 4: Summary of the performance of a hybrid solar cooker during cooking

Day	Insolation (w/m^2)	M_w (g)	T_{abs}	T_{pt}	T_{amb}	Wind speed(m/s)	Food	Quantity (g)	t_{cook} (Mins)
18.10.21	1008	280	82	68.9	34.5	0.0	Noodle	140	85
21.10.21	1200	560	64.9	70.1	36.1	1.2	White rice	280	150
6.12.21	1364	1640	83.1	96.1	38.1	1.0	Egg	5pcs (284)	90
6.12.21	1364	1640	84.6	100.8	38.3	1.0	Rice	820	120

Table 5: Maximum cooking power of the solar cooker

Mw(kg)	Cooking power (W)					
	1	2	3	4	5	6
1	213.5	210.7	209.3	207.2	207.4	203.7
1.5	337.1	339.2	343.4	345.5	345.5	347
2	375	381	333.5	387.8	392	385

1	160.3	172.2	183.4	189.7	193.9	247.8
1.5	162.7	163.8	199.5	197.4	190.1	189
2	278.6	292.6	298.2	326.2	352.8	350

Table 6: Maximum standardized cooking power of the solar cooker

Mw(kg)	Standardized Cooking power (W)					
	1	2	3	4	5	6
1	176.5	174	172.8	171	169	168.9
1.5	323.2	325	329	331	331.3	332.7
2	323.8	329	333.5	334.6	338.3	332.3
1	89.7	96.4	101.5	102.7	106.2	108.6
1.5	101.8	102.5	124.8	123.6	118.9	118.3
2	177.2	188.6	190.3	208.1	225.1	223.3

Table 7: Figure of merits

Parameter	First Figure of merit (F_1)	Second Figure of merit (F_2)
Day 1	0.17	0.44
Day 2	0.18	0.50
Day 3	0.10	0.35
Day 4	0.081	0.21
Day 5	0.091	0.28
Day 6	0.094	0.37

An integrated hybrid solar cooker was designed, constructed and evaluated. Table (1) and Figure (1) show the components and the exploded view of the hybrid solar cooker respectively. The stagnation temperature results are presented in Table (2) and Figures (2 – 7). Also, the results of the Water heating temperature are presented in Table (3) and Figures (8 – 13). Furthermore, controlled cooking test results are presented in Table 4 and cooking power results are presented in Table (5), the result for the standardized cooking power are presented in Table 6 and the figure of merit(s) are presented in Table 7.

The maximum stagnation temperature recorded by the cooker at the highest insolation of 1406W/m^2 with stagnation temperature of the absorber plate at 158°C and the pot temperature recorded was 167.4 °C and the corresponding ambient temperature recorded was 35.1°C. Similarly, findings were reported [10] with maximum insolation at 1075W/m^2 at a stagnation temperature of the absorber plate ranging from 108 - 124°C, temperature of the air inside the pot was 92°C while the ambient temperature recorded ranges between 32- 37°C.

The water heating test was carried out by boiling 1, 1.5 and 2 kg of water. It was observed that 1 kg of water boils faster than 1.5 and 2 kg respectively. It took 130 minutes for 1 kg of water to reach the boiling point of 105.3°C, it took 140 minutes for 1.5 kg of water to reach the boiling point of 101.6°C and lastly it took 149 minutes for 2 kg of water to reach the boiling point of 100.4°C. The result gotten is higher than the one reported [17] which took 90 minutes to boil 1 kg of water.

The cooking test was carried out using eggs, noodles, white rice and jollof rice respectively. It took 90 minutes to cook 5 pieces of eggs (284 g), it took 85 minutes to cook 140 g of noodles, it took

150 minutes to cook 280 g of white rice and it took 120 minutes to cook jollof rice. Similar result was reported [17] with data of 105 minutes to cook 200 g of noodles while jollof rice cooked at 180 minutes. It was observed that the cooking test performed better than the previously reported one as a result of incorporating a parabolic dish to concentrate more heat energy to the box cooker.

The first figure of merit (Day 2) has the highest figure of 0.18 and Day 4 has the lowest figures of merit which is 0.081 for both experiment 1 and 2. These values recorded was in accordance with the values earlier reported [9] which ranges between 0.10 to 0.15. Day 2 are classified as grade A cookers according to the criteria given in IS 134291(BIS, 2000a) while Day 1 cooker is classified to be in grade B.

The second figure of merit (Day 2) has the highest figure of merit of 0.50 and Day 4 has the lowest second figure of merit which is 0.21. These values gotten was in accordance with the values reported in literature [10] which range between 0.20 to 0.60. The F_2 for the cookers satisfied the requirements of IS 13429-1 (BIS, 2000a) by having F_2 up to 0.50.

The maximum cooking power attained by the hybrid solar cooker was 392W and the maximum standardized cooking power attained by the hybrid solar cooker was 338.3W. The result gotten was higher than the one reported in literature [18] stating that the maximum cooking power attained was 291W while the maximum standardized cooking power was 51W.

4. Conclusion

An integrated hybrid solar cooker was designed and constructed. It was experimentally tested and its performance was evaluated in terms of stagnation, water heating and cooking test. This work has shown the possibility of incorporating a hybrid solar cooker into a kitchen wall facing the direction of the sun, without stepping out of the building to harness energy. It was found to be more efficient and effective compared to the earlier ones done because a parabolic dish was incorporated to a box cooker in order to concentrate heat energy from the sun to the cooker box cavity.

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