IMPROVEMENT OF AN EXISTING SOLAR BOX COOKER IN RIVERS STATE

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ABSTRACT

A new 50cm X 50cm X 30cm solar box cooker was designed and fabricated. The new design is an improvement of an existing solar box cooker. The improvement focused on increasing the solar collector area of the existing type from $0.52m^2$ to $0.9171m^2$. The improved solar box cooker was evaluated by conducting no-load and load test and the solar cooking efficiency calculated. The results of the test showed a progressive increase in solar cooking chamber harvested temperature and cooking capacity over a period of 60mins and 100mins during no-load and load test conditions respectively. A solar cooking efficiency of 2.8% was obtained. The result further indicates that solar cooking can supplement fossil-fuel powered cooking.

Keywords: Solar energy, solar concentrators, solar box cooker.

INTRODUCTION

Lack of adequate energy supply that is cheap and accessible has been the subject of many scientific discussions across the globe. In the last one century alone, efforts have been geared towards exploring means of generating the desired energy to meet an ever increasing demand. Recently, the United Nations estimated that the world population will increase to about 10 billion people by 2050. Parallel to the population growth, the global energy requirement will rise considerably despite all further efforts concerning the rational use of energy (European Nuclear Society, 2014). According to estimates by the World Energy Council, in 2014, the world-wide primary energy consumption of currently about 12 billion tonnes coal equivalent per year will grow to a level of between 16 and 24 billion tonnes coal equivalent per year depending on the economic, social and political development by the year 2020. This, however, suggest that the per capita world-wide primary energy consumption which is currently at an average value of 1.5 tonnes of coal (equivalent to 33GJ) would continue to rise until world population peaks.

However, to meet the world per capita energy consumption, man has consistently explored his environment, making use of materials visibly seen either on the land or atmosphere or those tactically hidden in the ground as viable sources to meet his energy demands. These sources, according to Wikipedia (2014a), can be classified as fossil fuels (coal, oil, and gas); nuclear power; and renewable energy (hydroelectricity, wind power, geothermal, biomass and solar energy). Compared to renewable energy sources which are replaced faster than man can ever use of it, fossil fuels and nuclear power are considered as finite sources of energy meaning that they are depletable though they serve as the major contributors of world energy supply since the beginning of the industrial revolution. Today, fossil fuel and nuclear power alone contribute more than 90% of the total primary energy supply (Wikipedia, 2019a). However, the use of fossil fuels and the process of transporting, loading and enriching nuclear fuels for use at nuclear power stations have been linked to have a tremendous negative impact on the environment as a result of continuous increase in the amount of

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greenhouse gases deposited in the atmosphere daily. Global emissions of carbon dioxide from the combustion of fossil fuels were predicted to reach almost 36 billion tonnes at the end of 2013 by the Global Carbon Project. This amount, according to GCP (2013), was unprecedented in human history and that a continuation of the emissions growth trends observed since 2000 would place the world on a path to reach 2 degrees Celsius above pre-industrial times in 30 years. The impact of continuous CO_2 emissions into the atmosphere is currently being felt today as more alarming events that are consistent with scientific predictions about the effects of global climate change have become more and more commonplace. The rising sea levels, new heat and precipitation records, increase in the melting of glaciers around the world leading to severe floods and the increase in the outbreaks of infectious diseases in completely new areas are just a few of the impact of global climate change (Mimura, 2013). It is on this premise that researchers, policy makers and world organizations, are placing more emphasis on the need to harness the energy imbedded in renewable energy than fossil fuels and nuclear power. However, the calls for increased use of renewable energy has received a boost as new technologies capable of reducing carbon-based emissions, improve air quality as well as solve social problems related to use of fossil fuel have continued to emerge. Hydroelectricity, wind power, geothermal, biomass and solar energy are all renewable energy sources. Except solar energy sources, most forms of other renewable energy sources are expensive and do not provide cheap and easily accessible means of meeting the daily energy needs of man, particularly, for heating water and cooking food. Solar energy, when properly harvested through the use of simple materials, presents an excellent way of cooking food without paying for the energy utilized.

LITERATURE REVIEW

Cooking food differs considerably from heating water. This is so because under certain conditions, depending on the arrangement of the cooking facilities and heat source, a much higher temperature would be required to cook food than it is needed to heat water (Anon., 2019; Wikipedia, 2019b). Solar cooking technologies involve tapping the energy imbedded in the reflected rays of the sun through the use of materials of high reflective capacity that concentrate a large area of sunlight onto a smaller area to produce heat energy that can cook food(Crabtree and Lewis, 2007).

Achieving the desired temperature in the absorber compartment and retaining the heat so trapped is a subject of design. Can a well-designed solar cooker produce the much desired absorber temperature needed to cook food? Even when such a feat is achieved, would it be possible to have a well-designed solar cooker which can compete favorably with other types of cookers which use more stable forms of energy to cook food by just depending on the absorber temperature alone? Or could there be other design variables which are equally important as the absorber temperature that, when considered, would lead to a near perfect design of a solar cooker?

These questions will continue as long as most existing solar cookers today continue to show considerable lower cooking efficiencies than expected in the midst of several research efforts aimed at cushioning the effect. Having a well-articulated design procedure anchored on sound design principles may serve as the much needed link to improved solar cookers. An earlier research work (Nwankwo Solar Cooker 1) carried out by Nwankwo (2014) was reported to be defective as the total harvested solar cooking chamber temperature was a little higher than the ambient temperature and at such, it had low capacity to cook food. Based on this, the objectives of this research work will be to improve the first design (NSC1) by using an appropriate design methodology aimed at concentrating more heat onto the absorber to cook food, fabricate the improved design and assess the performance of the newly improved solar box cooker.

METHODOLOGY

Design Procedures

The design of a new model solar box cooker was undertaken as a result of the fact that an existing solar box cooker (NSC1) designed by Nwankwo (2014) performed poorly in terms of total harvested temperature in the cooking chamber and slow cooking which resulted into longer cooking times for staple foods like rice. According to Nwankwo (2014) that NSC1 had a maximum cooking chamber temperature of 50.5^{0}C and was seemingly able to cook food for 2hrs under fluctuating weather conditions. This, however, facilitated the need for improvement. The focus has been on using appropriate design techniques to increase the solar box cooking chamber temperature to a level where cooking can take place under optimal weather conditions. The section following will be dedicated to this. Also, selection of key materials and components that will facilitate the new design to perform optimally under different weather conditions will be carried out using appropriate design methodology.

Product Formulation

Product formulation precedes design. It is a formulated product that is subjected to design. The product so formed is a primary structure which does not necessarily contain all the features that will help it perform optimally but it can be fortified during design. The process of formulating a product for design is analogous to a lot of physical systems where constrains are set so that all that needs to be done at any particular point in time will be accomplished without breaking those limits. For the case at hand, formulating a product based on the basic concepts and principles of engineering will be adequate. Figure 1 shows a formulation of a solar box cooker.

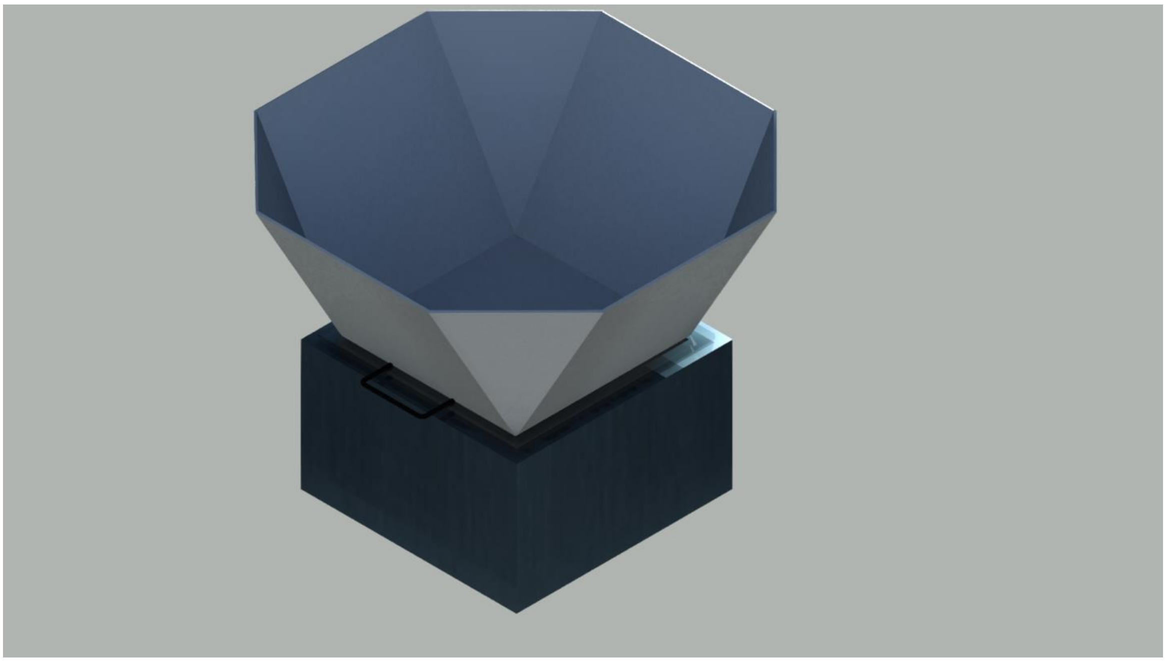

Fig. 1: A simple formulation of an improved solar box cooker.

It is a physical model that represents the law of conservation of energy so that when incident rays from the sun strikes the upper part of the structure, a fraction of the rays reflected into the lower part can be converted to heat. As more light rays from the upper part are reflected into the lower chamber, the conversion of light energy to heat will remain unabated. What amount of light rays is incident on the upper part and, of these incident rays, what fraction of it is reflected in the upward and downward directions? Of the rays reflected towards the lower part of the structure, what amount of it is converted to heat? Answers to these questions are a subject of design; hence the need to use an appropriate design methodology that guarantees reasonable results from its approach.

Design Considerations

The formulated structure, thought to be the improved solar box cooker, was put together without knowing how each of the components will contribute to the key objective of harvesting a higher solar cooker chamber temperature. Consequently, without the component by component design, it will be impossible to know whether the main objective will be achieved or not. The section following will dwell more on this. The cooker was considered to have the following components: eight solar collectors; a solar absorber facility (cooking pot); a clean transparent glass; a cooking chamber (solar box cavity); structural materials and insulation.

Solar Collectors

Essentially, solar collectors concentrate reflected incident sun rays onto an absorber which converts the light rays into heat (Wikipedia, 2014b). Most solar collectors are rectangular, square, spherical or parabolic shaped (Wikipedia, 2014c). The reflective property of solar collectors is obtained by coating the surface with silver, chromium or Aluminum or by just covering a chosen surface with Aluminum foil (Wikipedia, 2014b; 2014c). In the present work, flat, square and triangular shaped solar collectors with Aluminum foil surface covering were used.

Surface Area of Solar Collectors

Fig 1 shows eight solar collectors tilted at an angle of 60° to the horizontal. Four of the solar collectors are square with equal areas while the remaining four solar collectors are triangular in shape and are placed between any two square solar collectors directly perpendicular to the sun rays are also equal and are denoted as X_a and X_b respectively.

So that:

$$X_a = X_1 + X_2 + X_3 + X_4 \quad \ldots 2.1$$

Where

$$X_1 = X_2 = X_3 = X_4$$

And

$$X_b = X_5 + X_6 + X_7 + X_8 \quad \ldots 2.2$$

Where

$$X_5 = X_6 = X_7 = X_8$$

X_1, X_2, X_3 and X_4 are known as square shaped flat solar collectors having base and height dimensions of 40cm × 40cm, while X_5, X_6, X_7 and X_8 are known as triangularly shaped flat solar collector having base and height dimension of 34.64cm and 40cm respectively. Based on this, the total surface area of the combined solar collector is calculated as:

$$A_{\text{Total solar collector}} = X_a + X_b \quad \ldots 2.3$$

Four Square Collectors

1 square collector = 40cm × 40cm = 1,600cm^2

4 square collector = 4 × 1600cm^2 = 6,400cm^2

Four Triangular Collectors

1 triangular collector = (½× 40 × 34.64) cm^2 = 692.8cm^2

4 triangular collectors = 4 × 692.8cm^2 = 2771.2cm^2

$A_{\text{Total solar collector}}$ = 6400cm^2 + 2771.2cm^2
= 9171.2cm^2
= 9171.2 × 10^{-4}m^2
= 0.9171m^2

This value is significantly higher than that used by Nwankwo (2014). The aim of increasing the solar collector area is to concentrate more heat onto the absorber to improve its cooking capacity

Power Output of Gross Solar Collector

According to Renewable Heat Incentive (2014) that a solar collector can intercept up to 1000W/m^2 of heat at its surface on a clear summer day. This will mean that the total amount of heat available on the gross solar collector area of 0.9171m^2 will be:

Q gross solar collector = 1000W/m^2 × 0.9171m^2

Q gross solar collector = 917.1W = 0.9171kW

Ordinarily, all of this heat (0.9171kW) should have been concentrated onto the absorber (solar cooking pot). However, this is not possible due to incorrect tilt angle of the solar collector since the sun is in continuous motion; the direction the solar collector is facing, shading, and the efficiency of the solar collector (RHI, 2014).

RHI (2014) further suggested that only a fraction of this value (0.9171kW) reaches the absorber. To simplify the design problem, it is assumed that 70% of the heat interception by the solar collector is concentrated onto the absorber. So that:

$$Q_{\text{received by absorber}} = \frac{70}{100} \times 0.9171\text{kW}$$

$$Q_{\text{received by absorber from gross solar collector}} = 0.642\text{kW}$$

Heat Intercepted By Transparent Glass

The clean, transparent glass is placed horizontally and surrounded by the eight solar collectors (Fig. 1). The purpose of using a transparent glass is to intercept more sunlight into the cooking chamber which is then converted into heat thereby increasing the amount of heat available for cooking at the absorber as well as preventing convective heat loses through the top of the solar box (Wikipedia, 2014b). Hence, the amount of heat the transparent glass concentrates onto the absorber can be calculated by using the equation:

$$Q_{\text{Transparent Glass}} = I_a \ A_a \qquad \dots (2.4)$$

where

$Q_{\text{Transparent Glass}}$ = Heat concentrated by clear transparent glass (W)

I_a = Solar irradiance entering the collector Aperture (W/m^2)

A_a = aperture area of the collector (m^2)

Normally, the aperture area is smaller than the actual size of the glass.

The dimension of the transparent glass = 46cm × 46cm
= 2116cm^2
= 0.212m^2

Since A_a < 0.212m^2, we assume A_a as equal to 0.200m^2. Taking I_a = 1000W/m^2 and A_a =0.200m^2 and substituting into Equation (2.4), the amount of heat concentrated onto the absorber by the transparent glass is 1000W/m^2 × 0.200m^2.

$Q_{\text{Transparent Glass}}$ = 0.2kW

It is assumed that the heat loss from the cooking chamber of the solar box is negligible. Hence, the total amount of the heat available for cooking is:

$$Q_{\text{available for cooking}} = Q_{\substack{\text{received by absorber from} \\ \text{gross solar collector}}} + Q_{\substack{\text{received by absorber from} \\ \text{transparent glass}}} \quad \ldots (2.5)$$

$$Q_{\text{available for cooking}} = (0.642 + 0.2)\text{kW}$$

$$Q_{\text{available for cooking}} = 0.842\text{kW}$$

Dimensions of the Absorber (Solar Cooking Pot)

Though 0.842kW of heat is available for cooking from the combined heat of the gross solar collector and transparent glass, the effectiveness of this heat may amount to nothing if the absorber is not properly sized. To size the absorber, we utilize the geometric concentration Ratio (CR_g) as stated by Stine and Geyer (2014) as:

$$CR_g = \frac{A_{(\text{gross solar collector+transparent glass})}}{A_{Absorber}} \quad \ldots (2.6)$$

Since A $_{\text{(gross solar collector + transparent glass)}}$ >> A $_{\text{absorber}}$, $CR_g > 1$. Hence, CR_g is chosen as 10. Substituting this value into Equation (2.6), the surface area of the absorber can be obtained as:

$$A_{Absorber} = A_{\text{absorber}} = \frac{0.9171 + 0.2}{10}$$

$$A_{\text{absorber}} = 0.1117\text{m}^2 = 0.1117 \times 10^4\text{cm}^2 = 1117.1\text{cm}^2$$

$$A_{Absorber} = 0.1117\text{m}^2$$

$$A_{Absorber} = 1117.1\text{cm}^2$$

Now, with the fact that the absorber is the solar cooking pot, we will now design the pot. To do this, we know already that:

$$A_{\text{Total surface area of absorber}} = A_{\text{surface area of pot}} + A_{\text{top surface area of cover}} \quad \ldots 2.7$$

We choose a pot whose top cover has a diameter of 25cm

Hence,

$$\text{Top surface area of cover} = \pi r^2 = \frac{\pi D^2}{4} = \frac{3.142 \times (25)^2}{4}$$

$$= 491\text{cm}^2$$

Substituting the values of total surface area of the absorber and the top surface area of the cover into Equation (2.7), we will have that:

Surface area of pot + 491 = 1117

Surface area of pot = 626cm^2

Since the circular rim of the pot is assumed to be equal to the diameter of the top cover, the cut section of the pot will form an area of $\pi D \times$ H,

Where

D is the diameter of the top cover and

h is the depth of the pot.

Hence,

$\pi D \times \text{H} = 626\text{cm}^2$

$3.142 \times 25cm \times H = 626cm^2$

$$H = \frac{626cm^2}{3.142 \times 25cm}$$

$$H = \frac{626}{78.55} \times 1cm$$

$H = 7.96cm = 8cm$

Hence, a solar absorber (solar cooking pot) of size : height = 8cm and diameter = 25cm; were used.
Also, taking into consideration that the solar cooking pot will have to convert the transmitted sunlight into heat, it is considered that the absorber be painted black for effective heat absorption (Kyriakides, 2014).

Structural Materials

Structural materials are necessary so that the box will have proper shape and form so that it can be durable over time. To achieve this, the following structural materials were used: structural metal frame materials and structural metal sheet materials

Dimensions of Solar Box Cooker

A solar box cooker of dimension 50cm × 50cm × 30cm was chosen. This is to allow for adequate heating space for the absorber as well as aid the movement of the box from one place to the other easily during experimentation. The structure was framed and the external and base surfaces though painted black, were covered with fine metal sheets. This is to allow for insulation and maximum heat retention capacity within the box cavity.

Insulation

In order for the box cavity to reach temperatures high enough for cooking, the walls and the bottom of the box must have good insulation (heat retention) value. Based on this, cotton wool, a cheap and easily accessible commodity with good insulation capacity of 0.04W/m.K (Ferri et al., 2012) was chosen as the insulation material. A thickness of 5cm was considered adequate for the insulation.

The Designed Solar Box Cooker

Figure 2 shows an exploded view of the complete design of the improved solar box cooker. The complete design has a lot of features not mentioned in the formulated product hence showcasing it as an excellent piece for fabrication and performance evaluation.

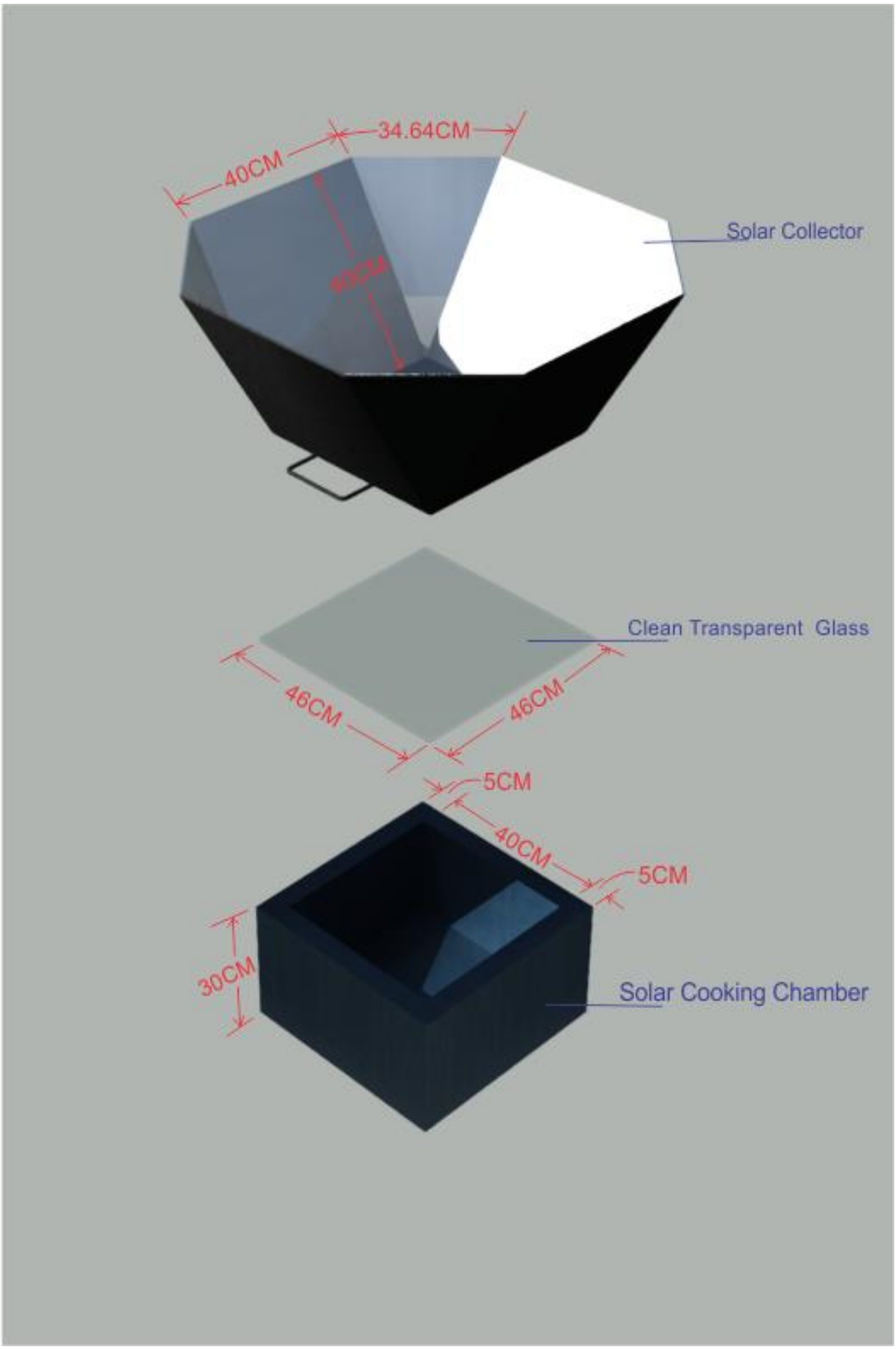

Fig. 2: A complete design of the improved solar box cooker.

Performance Evaluation

Testing and reporting of the results present an excellent way of evaluating the performance of a new model, particularly, for an improved solar cooker. However, the means of assessing the performance of the solar cooker should be made simple and can be easily understood by the common man. Based on this, the improved solar cooker was tested following the method suggested by Kundapur (1998) as:

$$\text{Solar Cooker Efficiency } (\eta) = \frac{M_w C_{pw}(T_{W2} - T_{w1})}{A_{sc}\int_o^t I_{aw}\Delta t} = \frac{Energy_{output}}{Energy_{input}} \quad ...(2.8)$$

where

M_w = Mass of water, kg

C_{pw} = Specific heat capacity of water (4.168kJ/kg K)

T_{w2} = Temperature of water (final), K

T_{w1} = Temperature of water (initial), K

A_{sc} = Aperture area of the solar cooker, m^2

I_{aw} = Insulation (average) W/m^2

Δt = Difference in time, s

No-Load Test

No-load test was performed by using water at a specified ambient temperature and temperature readings were taken by using a thermocouple until the water reached boiling point. The time taken to reach the boiling point was noted. This is shown in Fig. 3 below.

Fig. 3: The improved solar box cooker being exposed to solar radiation.

Load Test

Load test was performance by cooking two cups of rice in the cooker and the time taken to cook the food was considered.

RESULTS

At the end of the design and fabrication processes, the improved solar box cooker was tested under no-load and load conditions and the solar cooking efficiency was determined. The results of the test are presented in table’s 3.1-3.4 below and the results are discussed according.

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DAY 1: TABLE 3.1: Temperature of 0.5kg of Water Contained in the Absorber (Solar Cooking Pot)

TIME INTERVAL (Mins)	Temperature of Water at each Thermocouple			
	Thermocouple 1 Amb.Temp. $28^{O}C$	Thermocouple 2 Amb. Temp. $30^{O}C$	Thermocouple 3 Amb. Temp. $30^{O}C$	Thermocouple 4 Amb. Temp. $29^{O}C$
5	32	32	33	35
10	34	33	35	34
15	35	36	37	36
20	37	37	38	38
15	39	39	40	40
30	42	43	42	42
55	45	46	45	46
40	50	49	49	49
45	52	51	50	52
50	52	51	51	51
55	53	52	52	52
60	52	51	51	52

DAY 2: TABLE 3.2: Temperature of 0.5kg of Water Contained in the Absorber (Solar Cooking Pot)

TIME INTERVAL (Mins)	Temperature of Water at each Thermocouple			
	Thermocouple 1 Amb. Temp. $28^{O}C$	Thermocouple 2 Amb. Temp. $30^{O}C$	Thermocouple 3 Amb. Temp. $30^{O}C$	Thermocouple 4 Amb. Temp. $29^{O}C$
5	38	37	37	38
10	42	40	40	44
15	44	42	43	44
20	44	43	43	45
15	46	43	44	46
30	46	44	46	46
55	47	46	47	48
40	58	49	49	60
45	50	50	50	51
50	52	54	53	55
55	55	56	56	57
60	58	59	58	61

DAY 3: TABLE 3.3:Temperature of 0.5kg of Water Contained in the Absorber (Solar Cooking Pot)

TIME INTERVAL (MINS)	Temperature of Water at each Thermocouple			
	Thermocouple 1 Amb. Temp. $28^{O}C$	Thermocouple 2 Amb. Temp. $30^{O}C$	Thermocouple 3 Amb. Temp. $30^{O}C$	Thermocouple 4 Amb. Temp. $29^{O}C$
5	30	30	30	30
10	32	31	32	32
15	24	33	33	34
20	36	35	34	35
15	38	36	36	37
30	40	38	37	39
55	40	39	38	40
40	40	40	40	42
45	41	41	41	43
50	41	41	42	43
55	40	41	42	42
60	40	40	42	42

Table 3.4: Time Taken to Cook Two Cups of Rice

Time Interval (mins)	Physical Observation		
	Colour Change	Reduction in the Volume of Water	Food Texture
20	No visible change	No visible change in the water level	Hard
40	Slight colour change	No visible change in the water level	Hard
60	Colour changes but not yet white	Water level appears to become constant	Yielding to the compressive force of the fingers
80	Tends to approach white	Water level appears to remain constant	Slightly soft
100	Turns white	Water level appears to remain constant	Soft

DISCUSSION

A no-load test was conducted for three different days by using water at ambient temperature and the temperature of the water inside the solar cooking pot was taken with four different thermocouples after an interval of five minutes. Results of the test are presented in table 3.1-3.4 above.

Table 3.1-3.3 shows the result of the temperature distribution at four different points along the surface of the 0.5kg of water contained inside the solar cooking pot. The result showed gradual solar cooking during days 1-3. However, the cooking temperature increased gradually by day 2 with a minimum temperature of $37^{o}C$ after 5 minutes and peaked at $61^{o}C$ after 60 minutes. During this period, the water in the cooking pot showed light streams of water vapour escaping from the mass of water held inside the solar cooking pot thus suggesting that the temperature of the water increased significantly.

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Results of Load Test

Based on the fact that the results of the no-load test suggested that the temperature of the water inside the solar cooking pot could build up over a period of time if clear whether conditions are encountered, a load test was established by cooking two cups of rice. The result of the test is presented in table 3.4. Table 3.4 shows the result of the solar cooking test for two cups of rice. The result shows that no visible change of colour and water level as well as the texture of the food occurred during the first 20 minutes of the cooking experiment. However, as the cooking continued, slight colour changes were observed before the food eventually turned white after 40 minutes and 100 minutes respectively. During this period, the water level appeared to have reduced slightly before any change in the texture of the food was observed.

Solar Cooking Efficiency (η)

Basically, the solar cooking efficiency is a ratio of two energy terms: amount of total solar energy available at the surface of the glass and the fraction of this value that was absorbed by the water. The purpose of the design will have been achieved if the value of numerator approaches that of the denominator.

From Table 3.2, it can be seen that experimental results of day 2 appears to have the highest water temperature of 61^{o}C (334K) and invariably, represents a good value to use for our analysis. Experimental data corresponding to this point are:

Ambient temperature = 29^{o}C = 298K

Time taken to reach 61^{o}C = 60minutes = 3600sec.

Hence,

$$\text{The energy/sec. absorbed by 0.5kg of water} = \frac{0.5\text{kg} \times 4.168\text{KJ/kgK} \times (334-294)\text{K}}{3600\text{sec.}}$$

$$= 0.02315\text{kW}$$

$$= 23.16\text{W}$$

Hence,

Energy output per seconds = 23.16W

Nevertheless, the energy input per seconds was calculated as 0.842kW. Using these two values, we find the efficiency of the solar cooker as:

$$\text{Solar cooking efficiency } (\eta) = \frac{\text{Energy output per seconds}}{\text{Energy input per seconds}}$$

$$= \frac{23.16\text{W}}{842\text{W}} \times 100\% = 2.8\%$$

This value for the solar cooking efficiency appears to be very low. This could be attributed to the fact that the experiments were conducted in days when the weather conditions were very poor. Also, since it was difficult to align the cooker with the incident sun rays due to the continuous motion of the sun, lower solar cooker water temperatures were observed. This, notwithstanding, the true value of the solar cooking efficiency can be obtained in periods of clear sunny weather.

CONCLUSIONS

The objectives of this research have been to identify the areas that would need improvement in (NSC1), design and fabricate an improved solar box cooker and consequently, assess the performance of the improved solar box cooker. This informed the formulation of a new solar box cooker by considering an increase in the size of solar collectors, use of materials of better insulation capacity as well as those with good heat absorption tendencies to prevent heat reflected into the solar cooking chamber from escaping into the surroundings and to attract much of the heat in the solar cooking chamber to itself, respectively, in the design. A simple means was adopted to test the fabricated improved solar box cooker. The results presented in this research work, however, showed that by increasing the solar collector surface area, total harvested temperature within the solar cooking chamber was well above 60°C suggesting a significant improvement in the cooking capacity of the existing solar box cooker. Furthermore, the fact that the average cooking power has been enhanced supports the view of the authors of this research work that the improved solar box cooker can be readily used to prepare foods and sterilize contaminated objects.

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