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Performance Evaluation and Economic Analysis of a Domestic Solar Cooker

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Abstract

The thermal performance of a Domestic Solar Cooker (DSC) was evaluated in this study in accordance with the Society of Agricultural Engineers Standard (ASAE S58, 2003). The DSC is a parabolic solar cooker type with a focal point of 1 m, diameter of 2.14 m, absorber surface area of 0.07 m^2, concentrator surface area of 3.84 m^2, and concentration ratio of 54 which uses a glass mirror as its reflector. Results of the study show that stagnation temperature of 320˚C was attained at a heating rate of 5.4˚C/min. The first and second figures of merit values were 0.623 m^2K/W and 0.464 m^2K/W respectively, indicating that the DSC absorbs 31.82 J of radiated heat energy from the DSC in 1 second while the heat load (4 kg of water) absorbs 0.0512 J of the radiated heat for every degree rise in the pot temperature in a second. The cooking power of the DSC is 618.5 W, and the thermal efficiency is 48.67%. The solar insolation during the test is 453.81 W/m^2. This value is observed to be lower than what was obtained from similar solar cookers in published data implying that the DSC will perform better under higher solar insolation values. The cost of producing the DSC is N 12,920.00 (US$ 34) and with a payback time of 153 days, comparatively the DSC is judged to be viable economically.

Subject Areas

Chemical Engineering & Technology

Keywords

Solar, Cooker, Exergy, Evaluation, Economic, Analysis

1. Introduction

Cooking is an important aspect in human life, because the energy needed to carry out human activities is gotten from the food we eat. The main energy sources for cooking include: electricity, fossil fuel derivatives (Liquefied Petroleum Gas, kerosene), biomass (fuel wood, charcoal, animal dung, poultry droppings). These conventional sources have advantages of quick heating, availability, cost-friendliness, *et cetera*. However, demerits abound; for instance, the huge energy consumption of electric stove outweighs its advantage of quick heating. Also, the hazards associated with the use of Liquefied Petroleum Gas (LPG) make it dreadful to some persons, while the use of firewood and charcoal is the major contributor to deforestation and global warming. In the rural areas of Nigeria, biomass is the main energy source for cooking. This demand for biomass has led to increase in the rate of desert encroachment in the northern region as at least 3500 hectares of its arable land are lost annually to the desert [1]. The southern region of Nigeria is not left out of this negative effect as it has recorded an increase in the rate of gully erosion due to deforestation, which is an anthropogenic cause of gully erosion in this region [2]. An alternative to the use of fuel wood in the rural areas of Nigeria will be the use of solar cookers. Iwuoha and Ogunedo [3] opine that solar cooking is one of the simplest, safest, clean, environmentally friendly, and most convenient ways to cook without consuming conventional fuels or heating up the kitchen.

The technology employed in the design of solar cookers can be classified into 2 main groups based on the mode of operation: Concentrating type of solar cookers and Non-Concentrating type of solar cookers. Concentrating solar cookers operate by concentrating reflected rays of the sun on the absorber plate while the non-concentrating solar cookers heat up food substances by using greenhouse effect. **Figure 1** gives an illustration of the classification of solar cookers.

Solar oven cookers are also called solar box cookers. It is mainly a rectangular or square box with a transparent glass cover to trap sunlight into it, thereby utilizing the principle of greenhouse effect to cook. An insulator is introduced between the outer and inner walls of the oven in order to reduce heat losses from the bottom and sides of the cooker. The drawback of this type of cooker is the challenge of tracking the sun by changing the inclination of the mirror every 20 - 30 minutes [4].

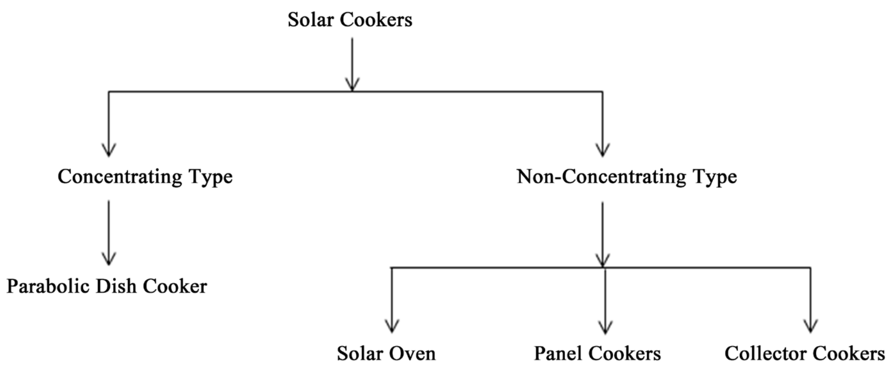

Figure 1. Classification of solar cookers.

The panel cookers are similar to the solar oven in design and principle of operation. However, it differs in the sense that it incorporates large reflective panels which focus sun rays on the cooking box glass cover, thereby increasing the temperature in the solar box more than what would be attained in the solar oven type. Studies [5] [6] [7] have shown that the efficiency of panel cooker can be enhanced using dual reflective panels. In a later study, Farooqui [8] showed that with an aspect ratio and optimized tilt angles of 2.66, 45˚ and 98˚ respectively, the cooker can operate for at least 6 hours a day without requiring solar tracking. Farooqui [9] also proposed another means of tracking system for solar cookers by using a gravity based tracking mechanism that drives a timing belt mounted on circular wooden disc. Result of the study shows that the system can help steady cooking for up to 6 hours per day before manual tracking is required.

The collector cooker is made up of three main parts viz: a flat plate solar collector, heating medium, and cooking pot. The flat plate solar collector is a very large heat absorbing plate, usually a large sheet of copper or aluminium chemically etched/painted black in order to effectively absorb the solar radiation for maximum efficiency. The heating medium is oil which runs in aluminium/copper pipes underneath the flat plate solar collector within an insulated enclosure. The absorbed solar radiations heat up the oil which then transfers the heat to the cooking pot through insulated aluminium copper pipe extended from the insulated enclosure to the cooking pot base where the absorber plate (cooking pot) is placed for food to be cooked. Farooqui [10] designed and constructed a vacuum collector cooker which utilized a one dimensional solar tracker to track the sun and has a thermal power transfer efficiency between 20% and 30%, while temperatures of up to 250˚C was achieved.

The parabolic dish cooker operates by concentrating solar radiations (through the aid of a parabolically shaped reflective surface) to the bottom of the absorber plate, causing heating of the pot to be achieved. The reflective surface could be made of Mylar sheet, polished Aluminium, glass mirror, *et cetera*. Parabolic cookers have been found to have an advantage of developing high temperatures for cooking. Ashok [11] noted that these cookers acquire concentration ratios of up to 50 and temperatures of up to 300˚C. Dasin [12] noted that concentrating cookers are the only class of solar cookers that are truly suitable for frying, as the temperatures at the focus can rival that of conventional electric gas or wood fired stoves. However, the low thermal efficiency of existing parabolic dish cookers within the rural areas of the country has become an impediment to the wide spread commercial use of the DSC. In view of the advantages DSCs offer, Iwuoha and Ogunedo [3] in their work opine that a domesticated application of solar cooking will help alleviate the demerits of fuel wood cooking. Therefore, in this study an evaluation of the thermal effectiveness of an existing domestic solar cooker and the comparative cost benefits thereof was carried out, establishing that at a thermal efficiency of 48.67% the study improved on previous work done by Dasin [12] in this area.

2. Materials and Method

The Domestic Solar Cooker (DSC) under investigation is designed using the technology of Concentrated Solar Panels (CSPs). Here, the sun rays are made to converge at a focal point through the aid of a reflective surface parabolic dish and the cooking pot (absorber plate) is usually positioned or located at this point. The component parts of the DSC are as follows: the parabolic dish (reflective surface), bracket (aids in manual tracking of the sun), dish stand, dish base, reflector material, cooking pot (absorber plate). The absorber plate is made up of Aluminum; the reflective material used is glass mirror, while other components are made of low carbon steel. Table 1 and Table 2 give information on the material selection and design specification of the DSC under investigation.

2.1. Evaluation Protocol

In carrying out the evaluation of the DSC, the method stipulated by Society of Agricultural Engineers Standard (ASAE S58, 2003) as presented by Funk [13] was adopted. Variables that affect the outcome of the test were classified into uncontrollable and controllable variables. Uncontrollable variables are those variables that cannot be manipulated by the operator because they are weather dependent. These include factors such as wind, ambient temperature, insolation, and solar altitude. Controllable variables refer to all variables that could be manipulated directly by the test operator during the test period. These include load

Table 1. Material selection.

S/n	Component Parts	Material Used	Reasons
1	Parabolic dish, Bracket, Dish stand, and Base.	Low carbon steel	Ductile and malleable. High tensile strength. Weld ability is high
2	Reflector	Glass mirror	High optical reflectance/heat transmittance.
3	Cooking Pot (Absorber plate)	Aluminium	Ductile and malleable. High resistance to corrosion. High thermal conductivity and food hygiene friendly.

Table 2. DSC design specifications.

Parameter	Value
Dish diameter	2.14 m
Dish depth	0.28 m
Dish stand	0.625 m
Concentrator total surface area (A_T)	3.84 m^2
Absorber surface area (A_s)	0.07 m^2
Reflectivity of reflector material	99%
Focal point	1 m
Concentration ratio (A_T/A_s)	54

value, solar tracking, and temperature measurement.

2.1.1. Uncontrollable Variables

The test was conducted between 10:00 and 14:30 hours (Nigerian Time) under clear sky condition because during this period, the solar zenith angle was moderately constant at the test location. The solar insolation values for the period of the test ranged from 452 W/m^2 to 463 W/m^2 with ambient temperature ranging from 33˚C to 36˚C. The temperature range was chosen because it allows for stability and repeatability of test results in any part of the country as most regions of the country experience the same temperature ranges. In order to ensure that the heat loss due to free air convection is kept at a minimum, and for achieving consistency in results, the tests were performed within the wind speed of 1.0 m/s to 1.39 m/s. Table 3 gives a summary of the test conditions for uncontrolled variables.

2.1.2. Controllable Variables

The load value refers to the mass of food product used during the test. 4 kg of water was used to test for the figures of merit, energy efficiency, cooking power and quality of the cooker. Manual tracking was employed during the test to track the movement of the sun. This is to ensure that the reflected rays are constantly focused on the absorber plate bottom (pot). Temperature readings for both sensible heating and stagnation tests were taken from the pot by making sure the probe of the digital thermometer is secured 10 mm above the pot bottom.

2.2. Performance Evaluation Procedure

The test location is Owerri with latitude of 5.4891˚N and longitude of 7.0176˚E. The test was conducted between 04/03/2018 and 24/03/2018 during clear sky days. The pot average temperature (T_p) during the determination of the first figure of merit and the average water temperature (T_w) during the determination of the second figure of merit were recorded every 10 minutes from 40˚C because within 10 minutes, it is assumed that the minor fluctuations in heat loss due to ambient temperatures and wind speed variability will be negligible, while the

Table 3. Test condition of uncontrolled variables.

Variable	Value	Reason	Measurement Instrument/Method used
Wind	1.0 m/s - 1.39 m/s	For minimum heat loss due to free air convection and consistency in test result.	MT130 cup anemometer
Solar Insolation	452 W/m^2 - 457 W/m^2	Minimize variability of results due to thermal inertia.	Mac Solar digital pyranometer
Ambient Temperature	33˚C - 36˚C	For stability and repeatability of results in other regions of the country.	TL8009 mini digital thermometer.
Test time	10:00-14:30 hours (Nigerian Time)	Moderately constant Solar Azimuth angle	Zenith Angle $=$ Latitude $-$ declination

heat gain variability due to gradual sun angle changes will be constant [13]. Also, at 40˚C, the water temperature is higher than the ambient air temperature, thereby creating condition for heat losses. The solar insolation (I_s) and ambient temperature (T_a) were recorded for corresponding temperature intervals.

Performance Indicators

First figure of merit (F_1)

This is also called stagnation temperature test. It gives information on the amount of the maximum temperature the pot can attain at a particular level of solar insolation. Mathematically, it is expressed as:

$$F_1 = \frac{T_p - T_a}{I_s} \tag{1}$$

where

T_p= Pot stagnation temperature,

T_a = Ambient air temperature,

I_s = Solar insolation on the horizontal surface.

The slope of the curve for F_1 against temperature difference gives information on the minimum area of the pot bottom needed to absorb 1 Joule of heat energy radiated to the pot from the solar cooker per second due to the temperature difference. This first figure of merit test was performed under a no load condition, *i.e.* the empty pot was placed on the pot stand while the sun rays were focused at the pot bottom.

Second figure of merit (F_2)

It quantifies the amount of heat that can be transferred from the pot to the load it contains. It could be called a sensible heating because during this test, heat is transferred from the pot to the water (load) without changes in the macroscopic variables of the pot. Mathematically, it is expressed using Equation (2).

$$F_2 = \frac{F_1 \left(M_w C_w\right)}{A \cdot \tau} \ln\left[\frac{\left(1-\left(T_{wi}-T_{av}\right)/\left(F_1 \cdot I_s\right)\right)}{\left(1-\left(T_{wf}-T_{av}\right)/\left(F_1 \cdot I_s\right)\right)}\right] \quad (2)\ [14]$$

where M_w and C_w = mass of the water in the pot and heat capacity of water respectively,

A = aperture area of the cooker,

τ = time difference during which water was heated from an initial temperature T_{wi} to the final temperature T_{wf},

I_s = average solar radiation on a horizontal surface, and

T_{av}= average ambient temperature during the experiment.

The second figure of merit was performed under a full load condition.

Cooking power (P)

This parameter indicates the sensible heat gain of the cooker, and it is the best indicator or measure of the cooker's ability to effectively heat food. This parameter is of great importance to the end users of the product. It is expressed mathematically as:

$$P = \frac{\text{Heat gained by load}}{\text{Heating time}} = \frac{M_w C_w \Delta T}{\tau} = \frac{M_w C_w \left(T_{wf} - T_{wi}\right)}{\tau} \quad (3)$$

Due to the climatic condition of the test location, the test was carried out with I_s below 700 W/m^2 therefore, in order to enable comparison of results from different locations and dates, Equation (3) was standardized by correcting it to a standard insolation of 700 W/m^2 as shown in Equation (4).

$$P_{std} = \frac{P \times 700}{I_s} \quad (4)$$

where P_{std}= Standard Cooking Power.

Equation (4) also known as standardized cooking power and is a suitable tool for comparative analysis between concentrated solar cookers.

Thermal energy efficiency (η)

The thermal energy efficiency indicates how the cooker utilizes the thermal energy in the reflected solar rays for heating. It is expressed as:

$$\eta = \frac{\text{Output}}{\text{Input}} = \frac{M_w C_w \left(T_{wf} - T_{wi}\right)}{I_s A \tau} \quad (5)$$

2.3. Exergy Analysis

According to Ogunedo and Okoro [15], exergy could be conceptualized to mean the maximum amount of energy available/maximum work that can be done by a system existing at a given state. It helps quantify losses in a system and identify locations where these losses occur. The indicators used for the analysis are explained below.

Exergy input (φ_i)

This is the maximum available energy from solar radiation to the solar cooker. It is expressed using Equation (6).

$$\varphi_i = I_s A \tau \left[1 + \left(\frac{T_a}{T_s}\right)^4 \left(\frac{1}{3}\right) - \left(\frac{4}{3}\right)\left(\frac{T_a}{T_S}\right) \right] \quad (6)\ [16]$$

where T_a and T_s, respectively, indicate the ambient air temperature during the experiment and the surface temperature of the sun

Exergy output (φ_o)

This is the amount of energy made available by the solar cooker for the purpose of heating. It was evaluated using Equation (7).

$$\varphi_o = M_w C_w \left(T_{wf} - T_{wi}\right) - M_w C_w T_a \ln\left[\frac{T_{wf}}{T_{wi}}\right] \quad (7)\ [15]$$

Exergy efficiency (ψ)

This gives an indication as to how the cooker can effectively utilize the available solar energy in heating food substances. It is expressed in Equation (8) as:

$$\psi = \frac{\text{Exergy output}}{\text{Exergy input}} = \frac{M_w C_w \left(T_{wf} - T_{wi}\right) - M_w C_w T_a \ln\left[\frac{T_{wf}}{T_{wi}}\right]}{I_s A\tau \left[1 + \left(\frac{T_a}{T_s}\right)^4 \left(\frac{1}{3}\right) - \left(\frac{4}{3}\right)\left(\frac{T_a}{T_S}\right)\right]} \tag{8}$$

Exergy loss (ϱ)

This is the amount of destroyed energy in the cooking device within the time under investigation. Equation (9) was used to determine this parameter.

$$\varrho = \varphi_i - \varphi_o \tag{9}$$

Exergy loss coefficient (ξ)

This is the amount of available energy destroyed per second due to systems irreversibility for every degree change in temperature between the heating load and ambient air over a square meter area of the dish. It is expressed using Equation (10).

$$\xi = \frac{\varrho}{A\tau\left(T_{wf} - T_a\right)} \tag{10}$$

The irreversibility of the system in this context means the heat loss due to rays not properly focused at the base of the absorber. This could be due to the nature of the reflective material used and the perfectness of the parabolic dish shape. The larger the temperature differences between the heating load and the ambient air, the lower the loss.

3. Result and Discussion

Table 4 gives the result of stagnation test carried out on the DSC. Results obtained from carrying out a 4 hours stagnation test on the DSC reveal that the maximum temperature attained by the pot is 320˚C and this occurred between 13:50 to 14:00 hours. From Figure 2, as the pot temperature (T_p) varies with time, heating to a stable temperature range of 300˚C to 320˚C by the DSC is done at an average rate of 5.4˚C/min. This means that the pot temperature increases by an average of 5.4˚C every minute until it attained 300˚C. The sun was manually tracked four times during the test, causing the DSC to have moved 60˚ away from its initial position (IP) at the start of the test.

A similar trend was observed for F_1 as shown in Figure 3. This is mainly due to the fact that F_1 is temperature dependent. The maximum and minimum values of F_1 are −0.002 m^{2}K/W and 0.623 m^{2}K/W occurring at 32˚C and 320˚C respectively. The negative value obtained as the minimum F_1 was because during the first 10 minutes of the experiment, the temperature of the pot was observed to be a degree lower than the ambient temperature.

Result of the relationship between F_1 and temperature difference between the pot temperature and ambient temperature as shown in Figure 4 reveal that 0.0022 m^2 area of the pot bottom absorbs 1 Joule of heat energy in 1 second. Hence, since the pot has an area of 0.07 m^2, it absorbs 31.82 Joules of radiated

Table 4. Stagnation test result.

Time	I_s (W/m^2)	Velocity (m/s)	T_p (˚C)	T_s (˚C)	Tracking angle
10:00-10:10	452	1	32	33	
10:10-10:20	452	1	98	33	
10:20-10:30	452	1	121	33	
10:30-10:40	452	1.1	201	33	S15˚W (IP)
10:40-10:50	453	1	298	33	
10:50-11:00	452	1.3	302	33	
11:00-11:10	452	1	302	33	
11:10-11:20	452	1	302	33	
11:20-11:30	452	1	300	33	
11:30-11:40	452	1	300	33	S30˚W from IP
11:40-11:50	452	1	300	33	
11:50-12:00	452	1	300	33	
12:00-12:10	452	1	300	33	
12:10-12:20	455	1	317	34	
12:20-12:30	455	1.3	311	34	
12:30-12:40	455	1.1	315	34	
12:40-12:50	455	1.3	301	34	S45˚W from IP
12:50-13:00	455	1.1	307	34	
13:00-13:10	455	1.2	307	34	
13:10-13:20	455	1.3	301	34	
13:20-13:30	455	1.3	300	34	
13:30-13:40	457	1	312	34	
13:40-13:50	457	1	316	35	
13:50-14:00	457	1	320	35	S60˚W from IP
14:00-14:10	457	1	318	35	
14:10-14:20	455	1	316	35	
14:20-14:30	453	1	307	35	

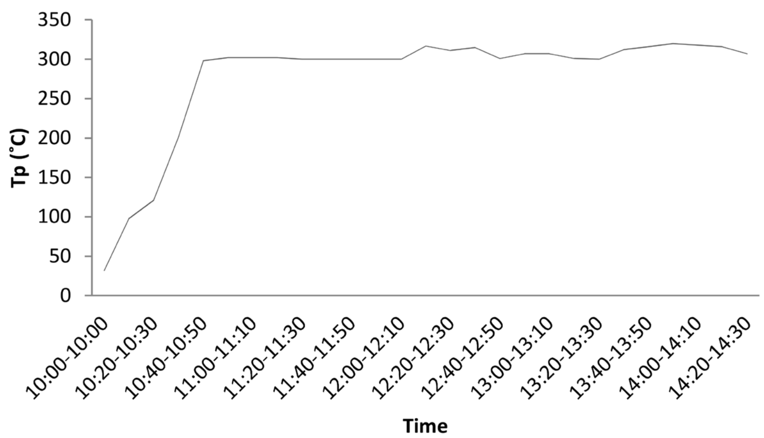

Figure 2. Variation of pot temperature with time.

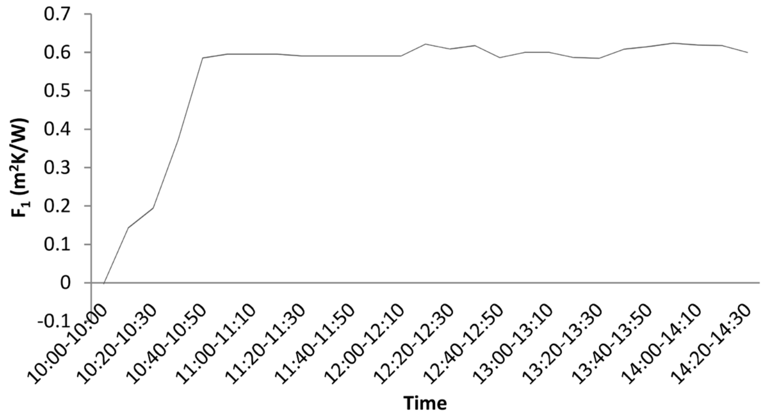

Figure 3. Variation of F_1 with time.

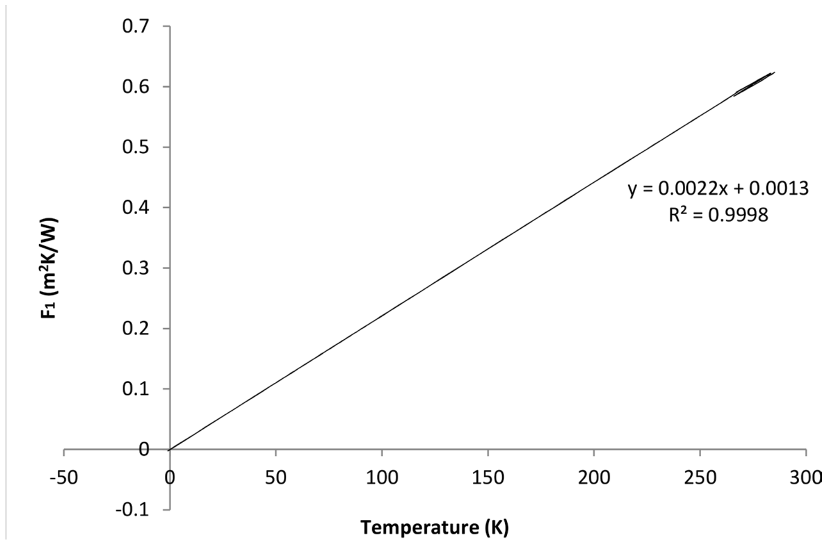

Figure 4. Variation of F_1 with temperature.

heat energy from the DSC in 1 second. These values obtained from F_1 show that at higher values of solar insolation, the DSC would perform brilliantly.

Equation (2) was used to determine the F_2 value of the DSC. The essence is to quantify the amount of heat absorbed by the load during the sensible test. **Figure 5** shows that 0.7316 W of heat is absorbed from the pot per m^2 for every degree rise in the pot temperature. hence, considering the area of 0.07 m^2 of the aperture where the pot is been positioned, it means that 0.0512 J of heat is absorbed by the heat load (4 kg of water) for every degree rise in the pot temperature in a second.

The standardized cooking power was determined using Equation (4). Then, a single measure of performance was generated by plotting a graph of the standardized cooking power against temperature difference between the heat load and ambient air. A standardized cooking power at a temperature difference of 50˚C is chosen as the cooking power of the DSC. A temperature difference of 50˚C was chosen because according to the results obtained in the work of Funk [13], it strikes a balance between overemphasis on the start-up cooking power and stagnation temperature, and is just below the critical temperature where cooking begins to occur. This is also the temperature where the solar cooker succeeds or fails. A regression model was fit for the determination of the standardized cooking power after collecting data from 22 tests. The model as shown in **Figure 6** and it reveals that the startup cooking power of the DSC is 1127.43 W, occurring at a temperature difference of 35˚C. From this point, the cooking power is projected to reduce by 31 W, with every 1˚C difference in temperature. Using the regression model fit for the data, the standardized cooking power of the DSC is 618.5 W.

The efficiency of the DSC was determined using equation 5. Average values of data obtained from 22 tests as shown in **Table 5** were used.

From the data obtained, the overall thermal efficiency of the DSC is 48.67%. This result is seen to be an improvement on an earlier work done in this area in Nigeria by Dasin [12] which had an efficiency of 17.5%. **Figure 7** shows a picture of the DSC in operation.

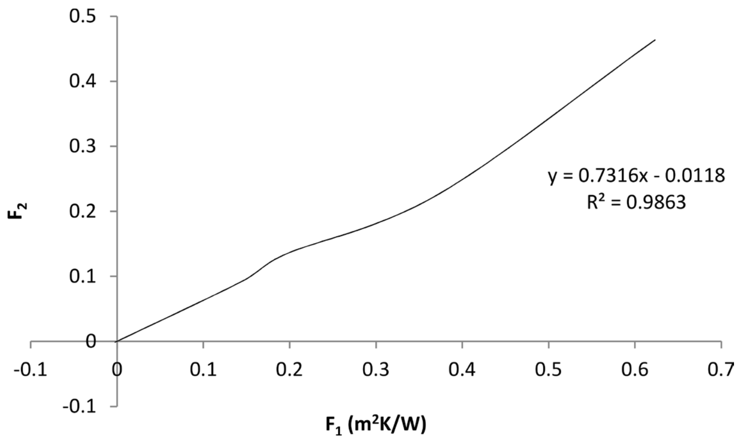

Figure 5. Variation of F_2 with F_1.

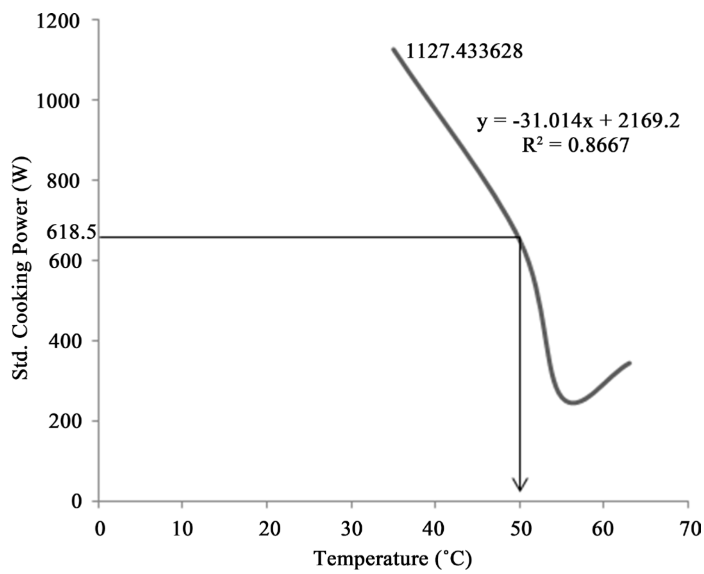

Figure 6. Variation of Std. Cooking power with temperature difference.

Table 5. Data obtained for computing thermal efficiency.

Condition	Average value
Initial water temperature (˚C)	41
Final water temperature (˚C)	96
Solar Insolation (W/m^2)	452
Mass of water (kg)	4
Specific heat capacity of water (kJ/kg˚C)	4200
Time (min)	10

Figure 7. Domestic solar cooker in operation.

Results of the exergy analysis carried out on the DSC show that due to the solar radiation flux, 313.87 J of exergy is inputted to the DSC. 95.03% of this input exergy is destroyed due to the irreversibility of the system leaving the output exergy at a value of 15.61 J, and exergy loss coefficient at 0.12. Hence, the actual potential possessed by the DSC to extract heat from its surrounding and reflect it to the cooking pot is 4.97%.

4. Economic Analysis

A breakdown of the cost of producing a unit of DSC is shown in **Table 6** as US$ 34 (N 12,920.00). The aim of the economic analysis is to determine the payback time of acquiring the DSC.

Table 6. Bill of Engineering Management and Evaluation Table.

Component	Cost
Parabolic dish	$12.50
Stand	$6.50
Castor wheels	$2.50
Base	$5.50
Pot stand	$4.00
Glass mirror	$3.00
Total	**US$34.00**

In the rural south-eastern areas of Nigeria where biomass such as animal dung and firewood is used, firewood of US$1 can cook 9 meals of beans for a family of 4. Beans meal is chosen for the analysis because of its longer cooking time than other staple foods. Considering an extreme case scenario, where 3 beans meals are served for a day, this means that US$1 can serve the cooking energy requirement for 3 days in a Nigerian family of 4 in a rural setting. However, considering the operating time of the DSC which is between 10 am to 3 pm, only two meals can be cooked per day. The energy payback time for the DSC is calculated on this premise using Equation (11).

$$\text{ʅ} = (n \times \text{Ʀ} \times \text{ƺ}) / \text{ƥ} \tag{11}$$

where

ʅ is the energy payback time,

n is the number of cooking days for US$1 cost of firewood,

Ʀ is the DSC acquisition cost,

ƥ is the firewood cost,

ƺ is the DSC cooking days factor = 1.5.

Using equation 11, the energy payback time is 153 days. This implies that DSC is low cost and economically viable and as a result, is suitable in the rural areas. Also, due to its passive nature, the cost of maintenance is reasonably low as only occasional lubrication of the brackets (which enables manual tracking) and cleaning of the reflective surfaces are the major maintenance works required.

5. Conclusions

This work evaluated the thermal performance of a domestic solar cooker (DSC) with parabolically shaped polished glass mirror reflective surface following the method stipulated in the ASAE S58 (2003) as stated by P. A. Funk in his solar energy works. The followings are the conclusions from the analysis of the data incorporating the parameters detailed in exergy technique:

- Evaluation of data obtained from 22 tested based on a chosen temperature difference of 50˚C and a regression model fit of the data established the standardized cooking power to be 618.5 W with an overall thermal efficiency of 48.67% which is a very far improvement on earlier result of 17.5% obtained by Dasin [5] with a similar DSC in Nigeria.

- Although the exergy potential of the DSC to extract heat from the ambient and reflect it on the pot is 4.97% (95.03% is dissipated), this serves as an area for improvement of DSC particularly on the perfectness of the parabolic shape.
- On the whole, these results are comparatively thermally stable, usable and point areas of attention for improvement to minimize system irreversibility and upgrade the exergy potential.
- The ease of use and quickness in meal cooking during sunlight days provide very viable alternative to other sources of fuel for preparing meals in the Nigerian rural setting once the initial finance investment of N12,920.00 (US$34) is made.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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