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To cite this article: A. O. Onokwai *et al* 2019 *J. Phys.: Conf. Ser.* **1378** 032065

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Journal of Physics: Conference Series **1378** (2019) 032065 doi:10.1088/1742-6596/1378/3/032065

Thermal Analysis of Solar Box Cooker in Omu-Aran Metropolis

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Abstract

Just like other solar cookers, the solar box cooker needs energy gotten from the sun to operate without producing emissions. In this research, a solar box is fabricated to reduce over-dependence on fossil fuel for energy generation. This reduces the environmental degradation caused by the use of other sources of energy. The ASHRAE empirical model was used to obtain the solar irradiance present in Omu-Aran metropolis. Thereafter, the no-load and load test was conducted to determine the cooker's thermal performance. The tests were conducted between January 2018 and January 2019 in Landmark University, Omu-Aran, Kwara State, Nigeria with geographical coordinates 8° 8' 0" North, 5° 6' 0" East. The average energy and exergy efficiency of the cooker were 32°C and 28°C respectively. A decrease in the efficiency of the cooker was observed. This was because the reflector, which is made from aluminium foil, was degrading. As a result of this degradation caused the sun rays (radiation) to be reflected poorly into the absorber and also caused a myth of overcast sky. Meanwhile, the variation in solar radiation during the sensible heating test resulted in the fluctuation inefficiency. The ratio of water to absorber temperature which was above 0.80 during the pre-boiling heating process indicates that the cooker can be recommended for sterilization.
Keyword: Energy, Exergy, Efficiency, Environment, Agriculture, Irradiance

1. Introduction

Energy is a focal point of every single human activity; without energy, present-day life would cease to exist. Beforehand, the interest in energy sources was unimportant. This was because it was basically used for cooking and other domestic purposes. However, with the passage of time, the demand for energy has increased due to increase in population, economic and technological advancement [1], [2], [3].

Since the industrial revolution, fossil fuel has become one of the primary energy sources used to drive improvements in technology. This phenomenon has resulted in an increase in air pollution so far [4], [5], [6]. In Nigeria, the rate of deforestation has risen up to about 400,000 hectares a year as a result of the usage of fuelwood. Following this trend, the forest resources of the country will be exhausted come 2020 [6]. In both rural and urban areas, access to a continuous supply of electricity is most times expensive. In 2003, it was established that less than 45% of the total population of Nigeria had access to electricity [7]. Also, most urban residents use kerosene and other by-products of crude oil for domestic cooking in spite of its consequent environmental threats. Notwithstanding, the danger of depletion posed by the usage of fossil fuels has triggered further exploration and development of alternative and renewable energy sources like solar energy [8], [9]. The incessant use of fuelwood has not only resultsed in deforestation but has been

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observed to also increase the mortality rate in rural areas. Searching for fuelwood not only costs the rural dwellers their time and energy but also the health of their women and children [10].

Renewable energy sources are considered as non – polluting sources of energy that have no inauspicious effect on the quality of the environment and produce the least secondary waste. They are also considered sustainable based on current and eventually future societal and economic needs [11], [12], [13].

According to Solar Cooker International, solar box cookers cook at appropriate temperatures. They most times accommodate multiple pots. They can get heated to a temperature of 140˚ C. Solar cookers cook food making use of only the radiation from the sun. With this, other conventional sources of fuel are saved to a large extent. It proves to be the safest, simplest and most appropriate way to cook food without making use of fossil fuels or raising the temperature of the kitchen unnecessarily. Before now, thorough research has been conducted on the various methods solar energy can be utilized.

As earlier stated, the solar box cooker needs energy from the sun to operate without producing emissions. Feasibility studies were conducted on the solar panel as well as the parameters of the solar cooker by [14], [15], [16]. It was observed that there was a change in weather conditions as a result of the variations of the solar radiations. This was due to the change in geographical locations in Nigeria. [17] described the factors that influence the performance of solar box cookers. It was also observed that solar cookers have good heat storage capability. The thermal performance of the solar cooker was tested using Mullick first and second figures of merit. This was conducted by [18], [19], [20], [20, [21]. In the work of [22], a hot box solar cooker that uses engine oil as its storage material was designed and manufactured. To check the performance of the cooker, conduction cooking trials and stagnation tests were performed. It was observed that both hot box cookers i.e. with and without storage material, had the same maximum stagnation temperature during the day. But this was not the case at evening time. According to the energy and exergy analysis on a box type solar cooker carried out by [23], the average exergy and energy outputs of the cooker were 2.5KJ and 21.6KJ respectively. [24] also investigated the proposed benchmark parameters of the solar cooker's thermal performance which are the time variations of instantaneous energy and exergy output of the solar box cooker.

A comparative study was also conducted on exergy and energy efficiency of solar parabolic cookers (SPC) and solar box cookers (SBC) by [23]. From the results, it was deduced that SPC had a higher energy and exergy efficiency compared to SBC. During the experimental period, it was observed that the energy and exergy efficiencies for the SBC ranged between 3.05–35.2% and 0.58–3.52% respectively. For the SPC, the energy and exergy efficiencies were between 2.79–15.65% and 0.4–1.25% respectively. Also, it was observed that there was a significant difference between the SBC and SPC when a statistical analysis using linear and polynomial regression was carried out.

[25] carried out an analysis of the energy and exergy efficiencies of solar parabolic cookers. In the work, we could see that the variation of the energy efficiency was credited to the thermal and optical losses from the pot and reflector, and also a change in environmental conditions. [26] performed an experimental investigation using varying reflector configuration, on the solar cooker's thermal performance. The results of the stagnation and sensible tests showed that using an aluminium cooking vessel is more efficient than using a stainless steel vessel.

Furthermore, there is inadequate information on the use of local materials and technology or the reuse of discarded materials for the design and development of a solar box cooker as an alternative and cheaper source of clean energy.

2. Materials and Methodology

A solar box cooker was designed and thermal performance was performed the experimental tests were carried out in the months of December 2017. Thereafter other tests were performed between January and December 2018 and lastly in January 2019 in Landmark University, Omu-Aran, Kwara State, Nigeria with geographical coordinates are 8° 8' 0" North, 5° 6' 0" East. The cooker comprises of various components such as box frame, plane reflector, double glass cover, absorber and insulator.

[27] was used to select materials for the fabrication of the cooker. The selection was based on its function, structural component, materials available, the properties of the materials, the shape of a structural component, the size of the structutral component, the process used to manufacture the structural component and cost.

2.1 Component and Materials Used.

2.1.1 Absorber Plate

The absorber plate received the solar irradiance that was transmitted through the double glass cover and converts the rays of light to heat being a black body. Matte black paint of 1mm thick was used because it serves as good absorber [28], [29], [30].

2.1.2 Reflector

The material used for the plane reflector was done according to [31], [32]. Aluminium foil was considered during the fabrication of the cooker because it was easily accessible, cheap, high reflectance/transmittance and good secularity and compatibility.

2.1.3 Box frame

The box frame is where all the heating activity is to take place as long as giving rigidity and shape to the system (the cooker). MDM Plywood was used instead of concrete because it has low thermal conductivity compared to concrete, less bulky, more flexibility during usage and more ergonomics during installation [33], [25].

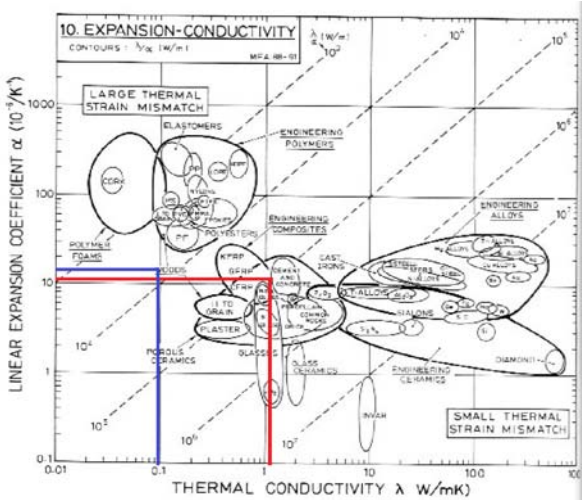


Fig 3.6- Thermal expansion coefficient vs Thermal conductivity of common materials [33]

2.1.4 Insulation

Despite the low thermal conductivity of plywood, it is still advisable to reduce thermal leaks from the inner chamber of the box cooker to the outer section of the box cooker. In order to achieve this,

insulative material is placed in between the layers of the inner and outer section of the box cooker. This material termed insulative is one that has a very low thermal conductivity. This will restrict the heat flow (natural heat convection) from the region of the higher heat to the environment (sink) of lower thermal energy. The choice of materials was done according to the method of [18]. Sawdust and chips from waste products of the chiselling process were used because they were readily available during the fabrication of the cooker.

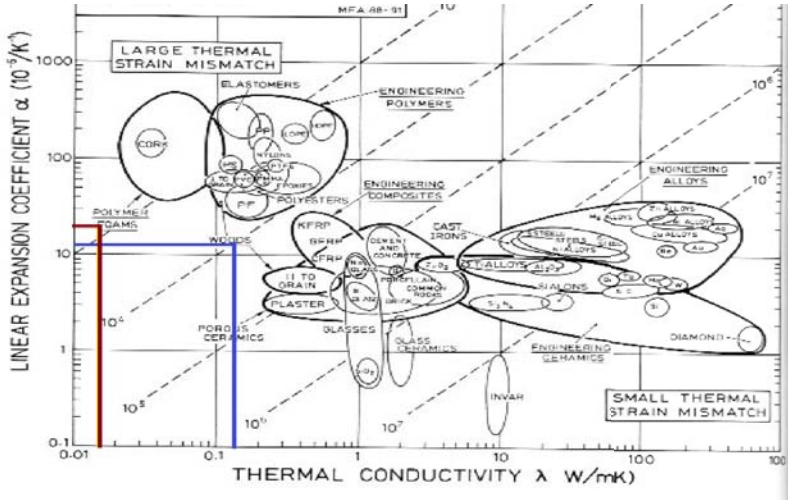


Fig 1. Thermal expansion coefficient vs Thermal conductivity of common materials [33]

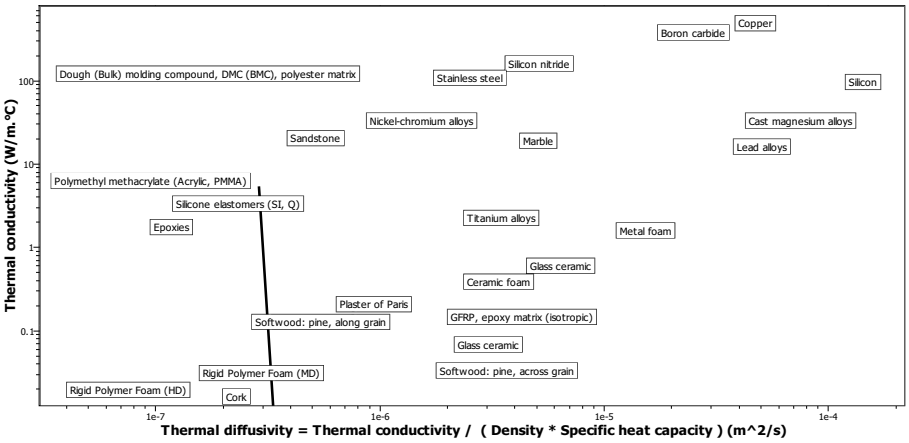


Fig 2. Thermal conductivity vs Thermal diffusivity of common materials [33]

2.1.5 Glass Cover

The glass cover is meant to be positioned in the box cooker for receiving the sun's radiation from the plane reflector. mechanically stronger and harder, has high resistant to thermal shock, can be shaped easily into vacuum insulated and more chemically resistant to Acids [25], [33].

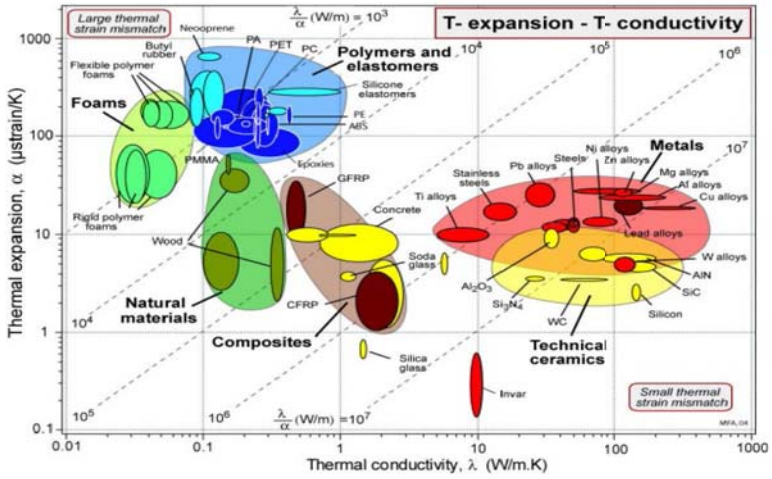


Fig 3. Thermal expansion coefficient vs Thermal conductivity of common materials [33]

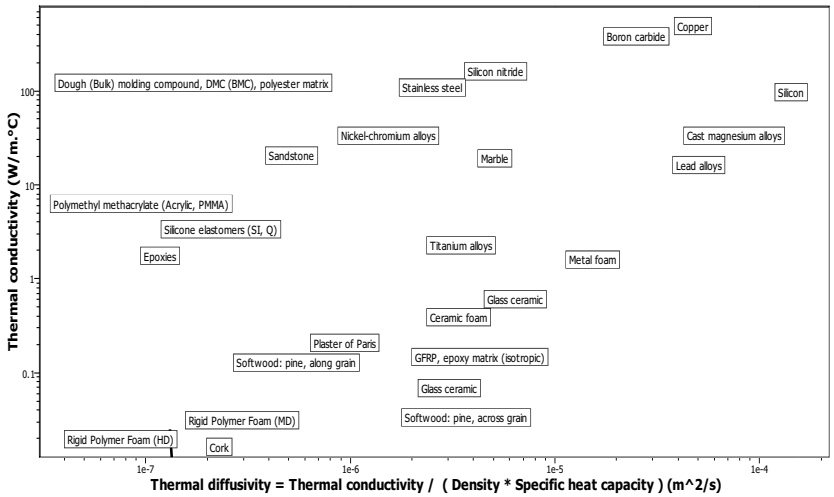


Fig 4. Thermal conductivity vs diffusivity of common materials [33]

2.2 Construction of Solar Box Cooker

The solar box cooker is made of a wooden frame, a solar absorber, a wooden cover and a reflector. Each of these parts has been designed carefully and constructed together to make the solar box cooker.

The frame is made from MDM plywood with a thickness of 3/4 in (1.905 cm). The shape of the frame is in the form of a cuboid without a top. The long faces of the cuboid measure 53.81cm by 50 cm. The shorter faces of the cuboid measure 50cm by 50 cm. The plan view and the sectional view of the frame is shown in Figure 4(a) and 4(b) respectively. A picture of the constructed wooden frame without the bottom sheet and cover is shown in Figure 5. The bottom sheet is made from china plane wood and has a thickness of ¼ in (0.635 cm). Aluminium foil is used to line the inside of the frame. This is because aluminium foil retains heat within the box by making the thermal energy that gets to the inner surface of the frame to bounce back.

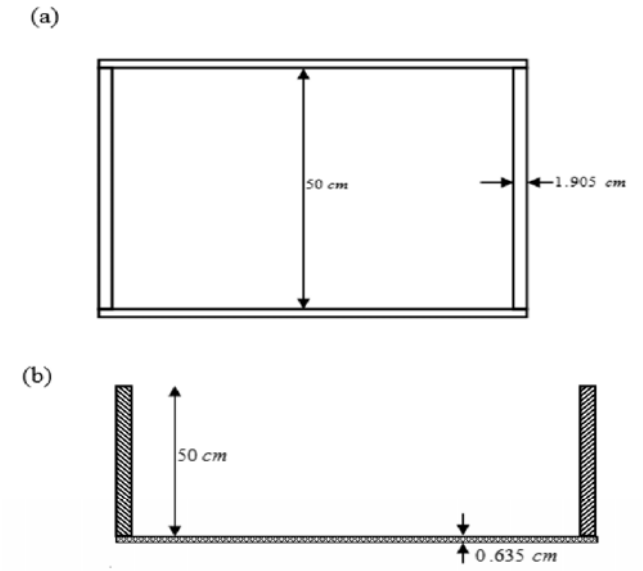


Figure 4: A plane and sectional drawing of the wooden frame with dimensions



Figure 5: A picture of the wooden frame without the bottom wooden sheet showing the details of the plywood used

The solar absorber is made from smooth aluminium with a thickness of 0.54mm. It is fabricated as an inverted square – based pyramidal frustum as shown in Figure 6. The dimensions of the frustum are depicted in the figure. The length of frustum's slanting sides is calculated using the length of the other sides (gotten from Figure 6) and Pythagoras rule. It is thus given as $\sqrt{15^2 + 7.5^2} = 16.77$cm. The wooden frame base is covered with spiral/ helical shaped wooden chips. The wood chips are waste products gotten from the chiselling process. Sawdust is then used to cover the chips to serve as a layer of insulation which is 5cm thick. The 35 by 35 cm square base of the frustum (solar absorber) is then placed on the base insulation layer. The 3D design of the Solar Box Cooker is shown in Figure 7. The space between the slanting sides of the absorber and the inner surfaces of the wooden frame is filled with a composition of chiselled wooden chips and sawdust. The process is shown in Figure 8.

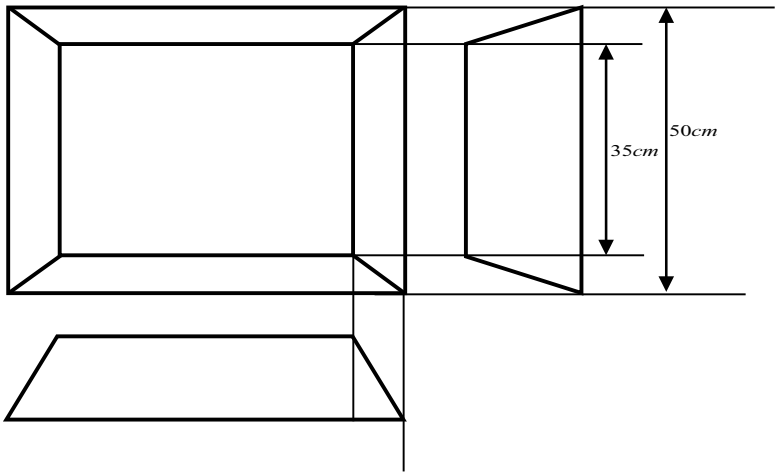


Figure 6: Drawing of 0.54mm thick smooth aluminium solar absorber constructed as an inverted square – based pyramidal frustum

The cover of the solar box cooker is a wooden frame constructed to hold two glasses (double glazing) and a reflector. To prevent heat loss from the cooking chamber, an airtight cover is needed. For this reason, rubber gotten from discarded motorcycle tubes are placed between the glass and the support surface. This also minimizes fragility. The reflector is made from china plane wood with a thickness of 0.5in (1.27cm) covered with aluminium foil. The cover also has a square aperture of size 47.3 cm. To allow tilting, an aluminium sheet is used to attach the reflector to the cover. Also, a wooden lever was constructed in order to hold the reflector in position. Rubber materials are used to line the contact surface between the cover and wooden frame as shown in Figure 9. This is to make sure the solar box cooker is airtight. The aluminium sheet used to make the solar absorber as well as the outside of the cooking pots is painted matte black as shown in Figure 9 [31]. They are painted matte black so as to convert the rays of light transmitted through the glass cover to heat.

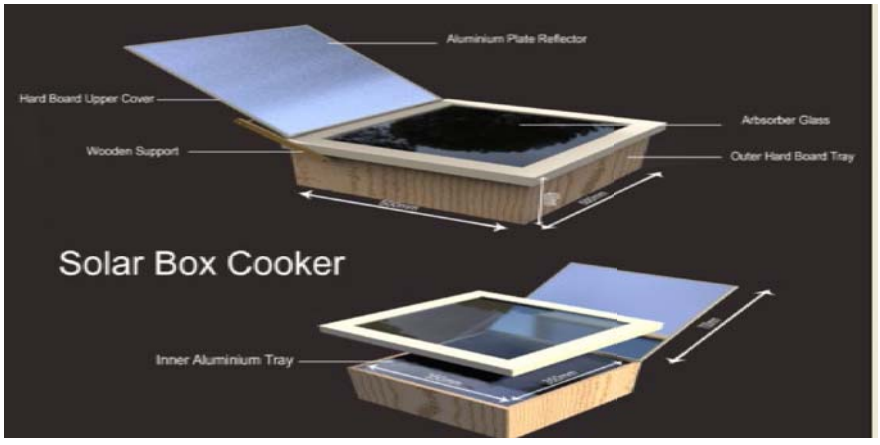


Figure 7: 3D Design of the Solar Box Cooker



Figure 8: A picture showing the process of insulating the cooker with chiselled wooden chips and sawdust



Figure 9: A picture showing the aluminium sheet of the absorber and cooking pots painted matte black. It also shows the rubber material used to line the contact surface.

2.3 Energy Gain of Solar Cooker

The solar box cooker energy gain was divided into three parts, namely; solar energy striking the glass cover, Solar Energy Transmitted through Glass Cover and Thermal Energy Generated by the Absorber [34], [18].

2.3.1. Solar Energy Incident on the Glass Cover

Solar Energy striking the glass cover is divided into three parts namely; diffuse solar irradianceI_d, beam solar irradiance I_b and reflected solar irradiance I_r. The total solar irradiance was calculated using eqn. (2.1-2.4).

$$I_T = I_b + I_d + I_r \tag{2.1}$$

$$I_b = Ae^{-\frac{B}{\sin\alpha}} \cos\theta_g \tag{2.2}$$

$$I_d = ACe^{-\frac{B}{\sin\alpha}} \cos\theta_g \tag{2.3}$$

$$I_r = \left(\rho_r cos\theta_{rg}\right) A e^{-\frac{B}{\sin\alpha}} \cos\theta_r \quad (2.4)$$

2.3.2. Solar Energy Transmitted through Glass Cover

The total amount of energy that is transmitted through the glass cover and enters the cooking chamber is directly proportional to the total amount of solar irradiance striking the glass cover. The solar energy transmitted through the glass cover was calculated using eqn. (2.4- 2.8). This energy was divided into three parts; the beam transmitted solar irradiance I_{bt}, diffuse transmitted solar irradiance I_{dt} and reflected transmitted solar irradiance I_{rt} [34], [18].

$$I_{Tt} = I_{bt} + I_{dt} + I_{rt} \quad (2.5)$$

$$I_{bt} = \tau_{bt} A e^{-\frac{B}{\sin\alpha}} \cos\theta_g \quad (2.6)$$

$$I_{dt} = \tau_{dt} AC e^{-\frac{B}{\sin\alpha}} \cos\theta_g \quad (2.7)$$

$$I_{rt} = \tau_{rt}\left(\rho_r cos\theta_{rg}\right) A e^{-\frac{B}{\sin\alpha}} \cos\theta_r \quad (2.8)$$

Where τ_{bt}, τ_{dt} and τ_{rt} are respectively the transmittances of the glass cover to beam, diffuse and reflected solar radiation striking the glass cover.

2.3.3. Heat Energy Generated by the Absorber

The solar energy converted to heat by the absorber in the cooking chamber is proportional to the absorptance of the absorber to the various components of the transmitted radiation. This energy; diffuse transmitted solar irradiance q_{dt} and reflected transmitted solar irradiance q_{rt} and beam transmitted solar irradiance q_{bt} can be calculated using eqn. (2.9-2.12).

$$q_T = q_{bta} + q_{dta} + q_{rta} \quad (2.9)$$

$$q_{bta} = \alpha_{bt} \tau_{bt}^2 A e^{-\frac{B}{\sin\alpha}} \cos\theta_g \quad (2.10)$$

$$q_{dta} = \alpha_{dt} \tau_{dt}^2 AC e^{-\frac{B}{\sin\alpha}} \cos\theta_g \quad (2.11)$$

$$q_{rta} = \alpha_{rt} \tau_{rt}^2 \left(\rho_r cos\theta_{rg}\right) A e^{-\frac{B}{\sin\alpha}} \cos\theta_r \quad (2.12)$$

Where α_{bt}, α_{dt} and α_{rt} are respectively the absorptance of the absorber to beam transmitted, diffuse transmitted and reflected transmitted solar radiations within the box or cooking chamber.

2.4 Energy and Exergy Analysis

2.4.1 Energy Analysis

The energy input, E_i to the solar cooker, was obtained using eqn. 2.13 while the energy output, E_o was calculated using eqn. 2.14 [35]

$$E_i = I_{av} x A_{ap} \quad (2.13)$$

$$E_o = M_w C_w \frac{(T_f - T_i)}{dt} \quad (2.14)$$

The energy efficiency was given as

$$\eta = \frac{E_o}{E_i} = \frac{Energy\ output}{Energy\ Input} \quad (2.15)$$

2.4.2 Exergy Analysis

The exergy input, exergy output and exergy efficiency were calculated using eqn. 2.16, 2.17 and 2.18 respectively [35], [36], [37], [38].

$$Ex_i = I_s\left[1+\frac{1}{3}\left(\frac{T_{ab}}{T_s}\right)^4-\frac{4}{3}\left(\frac{T_{ab}}{T_s}\right)\right]A_{ap} \tag{2.16}$$

$$Ex_o = \frac{M_w.C_w\left[\left(T_f-T_i\right)-T_a In\frac{T_f}{T_i}\right]}{dt} \tag{3.17}$$

$$\varphi = \frac{Ex_o}{Ex_i} = \frac{\dfrac{M_w.C_w\left[\left(T_f-T_i\right)-T_a In\frac{T_f}{T_i}\right]}{dt}}{I_s\left[1+\frac{1}{3}\left(\frac{T_{ab}}{T_s}\right)^4-\frac{4}{3}\left(\frac{T_{ab}}{T_s}\right)\right]A_{ap}} = \frac{Exergyoutput}{Exergyinput} \tag{3.18}$$

2.5 Experimental Set-up and Procedure

- ✓ The tests and checks were conducted between the hours of 10:00 am and 5:00 pm.
- ✓ The cooker was shielded from direct sunlight by keeping it under a shade before carrying out the tests and then later brought out to receive solar radiation.
- ✓ The performance of the cooker was then tracked manually every ten minutes.
- ✓ During the no-load (stagnation) test, the thermocouples were connected to the centre of the absorber plate at the bottom. During the boiling test, they were immersed in water.
- ✓ 2 litres of water, shared equally into two homogenous pots, was used each time the load test (sensible test) was conducted.
- ✓ The Campbell Scientific LTD Anatomy of a Weather Station, installed in Landmark University Omu-Aran, Kwara State was used to take measurements of the solar radiation, wind speed, wind direction and the direction of the sun.
- ✓ Also, the 4 Channel digital data logging thermometer, connected to K-Type thermocouple was used to take measurements and keep a record of the ambient temperature.
- ✓ The results were then logged every ten minutes [18], [25].

3.0 Results and Discussion

Figure 10 shows the graphical representation of the average clear-sky solar irradiance of the beam, reflected and diffuse solar irradiance. The beam solar irradiance is the solar radiation travelling from the sun down to the surface of the earth on a straight line. The diffuse solar irradiance is the solar irradiance that has been deflected by atmospheric molecules and particles, but has still made it to the surface of the earth. The reflected irradiance is the solar irradiance that has been reflected off from non-atmospheric surfaces such as ground (www.ftexploring.com). Also, it can be seen that the beam irradiance and diffuse irradiance are maximum at 12noon, while there was no reflected irradiance at 12noon. The reflectors are tilted in the direction of the sunlight until when it is 12noon. At this point, the plane and parabolic reflector have no row to play as the irradiance travels directly into the solar box at 90^o [25].

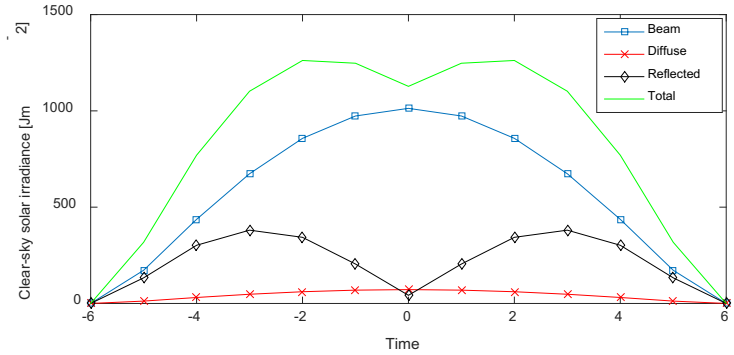


Figure 10. Average I_b, I_d, I_r and I_T in the Month of December 2017 obtained from ASHRAE models.

The figure below (Figure 11) shows the graph of the average beam, diffuse and reflected of noon clear-sky transmitted solar irradiance for irradiance. From the graph, it can be seen that the transmitted solar irradiance increased gradually and got to the peak at 12 noon for both the average beam and diffuse solar irradiance. However, the reflected irradiance experienced no transmittance.

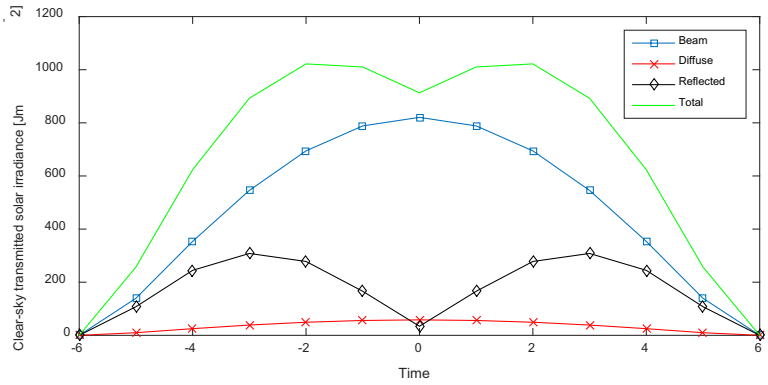


Figure 11 Average Clear-sky transmitted irradiance (I_{bt}, I_{dt}, I_{rt} and I_{Tt}) in the Month of January 2018 obtained from ASHRAE models

Figure 12 is a graph showing the minute variation in clear sky heat generation rate with relatively bright sunshine observed in the month of September 2018. In the mornings, the sky was a bit cloudy until 11:20 am (GMT +1) when the sky became clear with bright sunshine. At 12 noon (GMT +!), the cookers generated maximum heat.

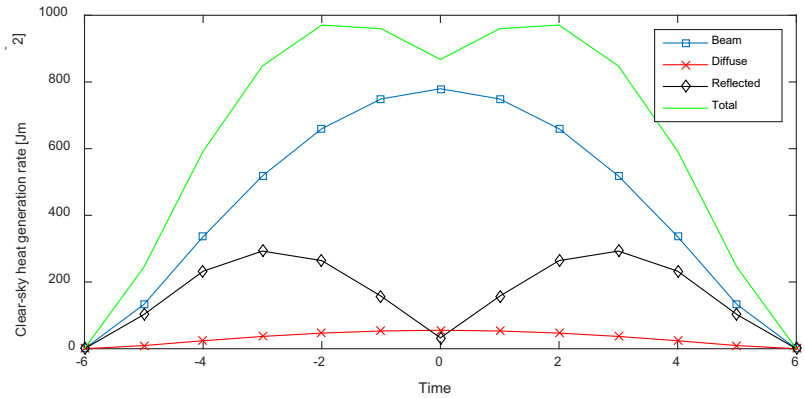


Figure 12. The clear-sky heat generation rate (q_{bta}, q_{dta}, q_{rta} and q_T) for 15th of September 2018 obtained from ASHRAE models.

Figure 13-15 shows the results of the no-load test carried out on 9th April and 3rd June 2018. Figure 16-17 shows the results of the load-test on 8th May and 3rd June in Omu-Aran, Kwara State. Generally, the peak stagnation temperature was recorded between 12:30 pm and 1: 30 pm. This stagnation temperature remained steady till 3:50 pm after which it decreased gradually as a result of an increase in wind speed/humidity and a decrease in solar irradiance. Also, the temperature change of the solar absorber and that of the cooker chamber can be seen to closely follow the clear – sky transmitted irradiance. The rough nature of the graph of the temperature of the absorber and the cooker chamber was due to a poor, cloudy sky and random weather. These maximum values were recorded at 13:30 pm (GMT +1). The ambient temperature at this time was 32.19^{o}C. The absorber temperature was consistently higher than the chamber temperature as expected. This is because the solar absorber is the source of heat. It can also be seen that the temperature of the chamber and absorber of the solar parabolic cooker is higher compared to that of the solar box cooker under the same weather condition, period and surface area, as presented in Figure 4.12 to 4.30. This is because the reflector area was fully utilized as it is a fully steerable dish system. Therefore, there were no losses due to the aperture projection effects. Also, because of the small area of the absorber at focus, the radiation losses were small [39].

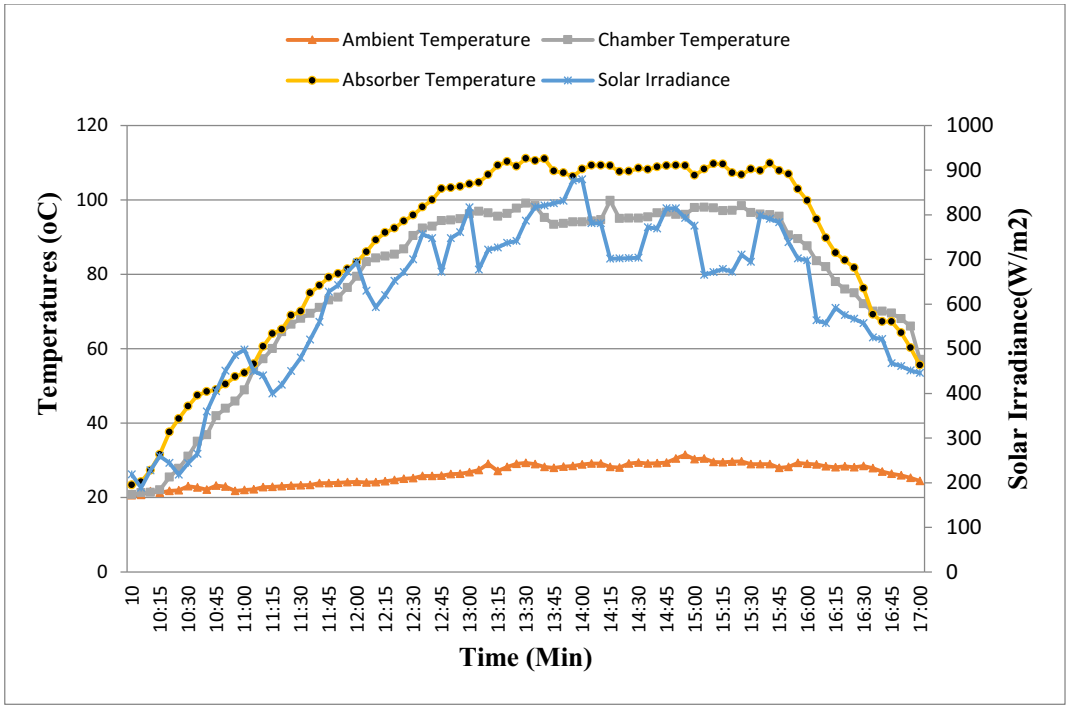


Figure 13. Average Temperatures against Time during Stagnation Test on 9th April 2018

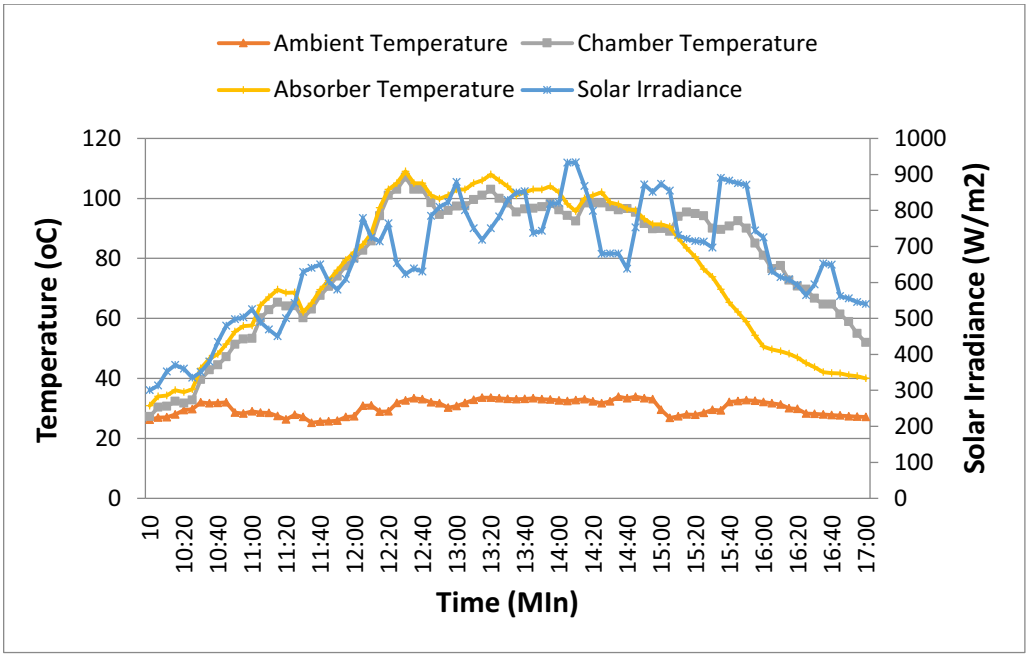


Figure 15: Temperatures against Time during Stagnation Test for Box Cooker on 4th June 2018

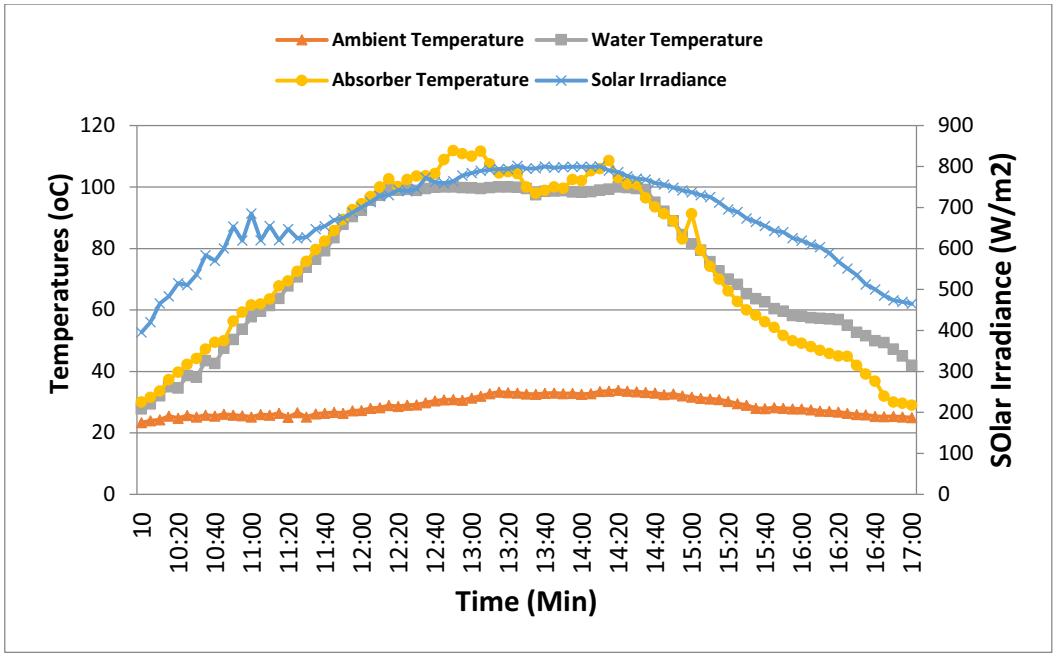


Figure 16: Temperatures against Time during Sensible Test for Box Cooker on 8th May 2018

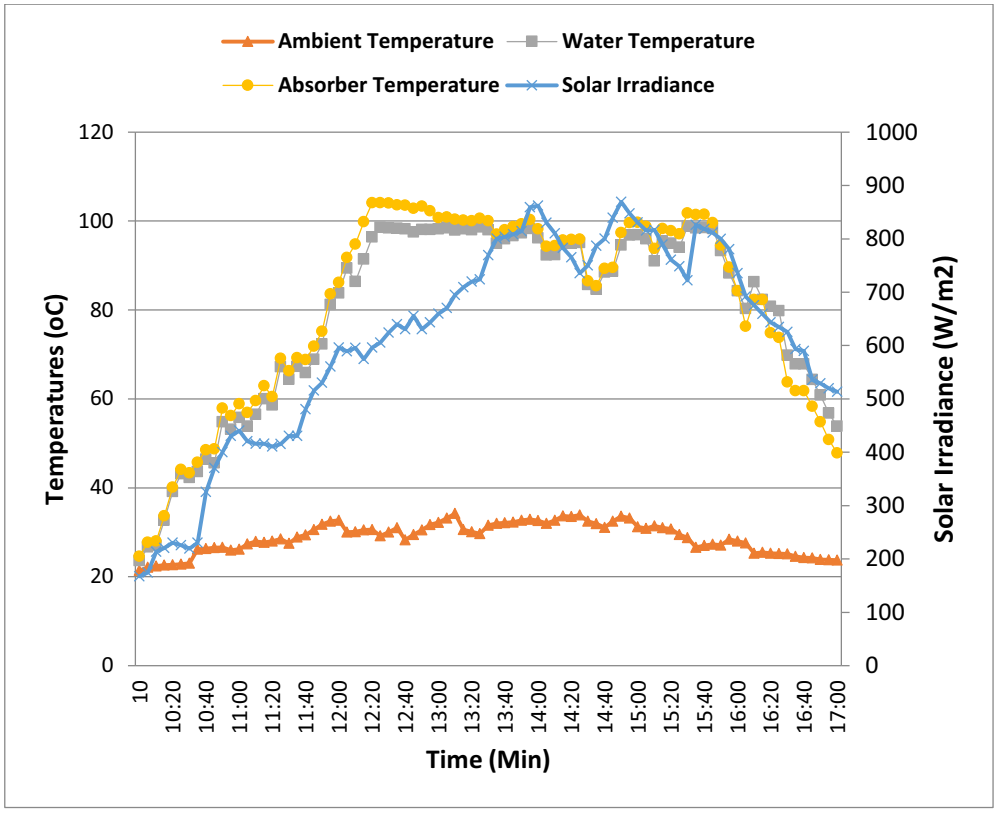


Figure 17: Temperatures against Time during Sensible Test for Box Cooker on 3rd July 2018

Fig 18 shows the effect of temperature difference on exergy and energy efficiency the solar box cooker. The exergy and energy efficiency of the cooker increases steadily initially to a peak point at 17 K and then decreased gradually as the difference in temperature decreased. The figure shows that the solar box cooker can retain water in the pot higher than the ambient temperature, thus making the cooker effective for heating [23]. Increase in the exergy and energy efficiency of the cooker was attributed to the ability of the absorber to convert the solar irradiance to heat.

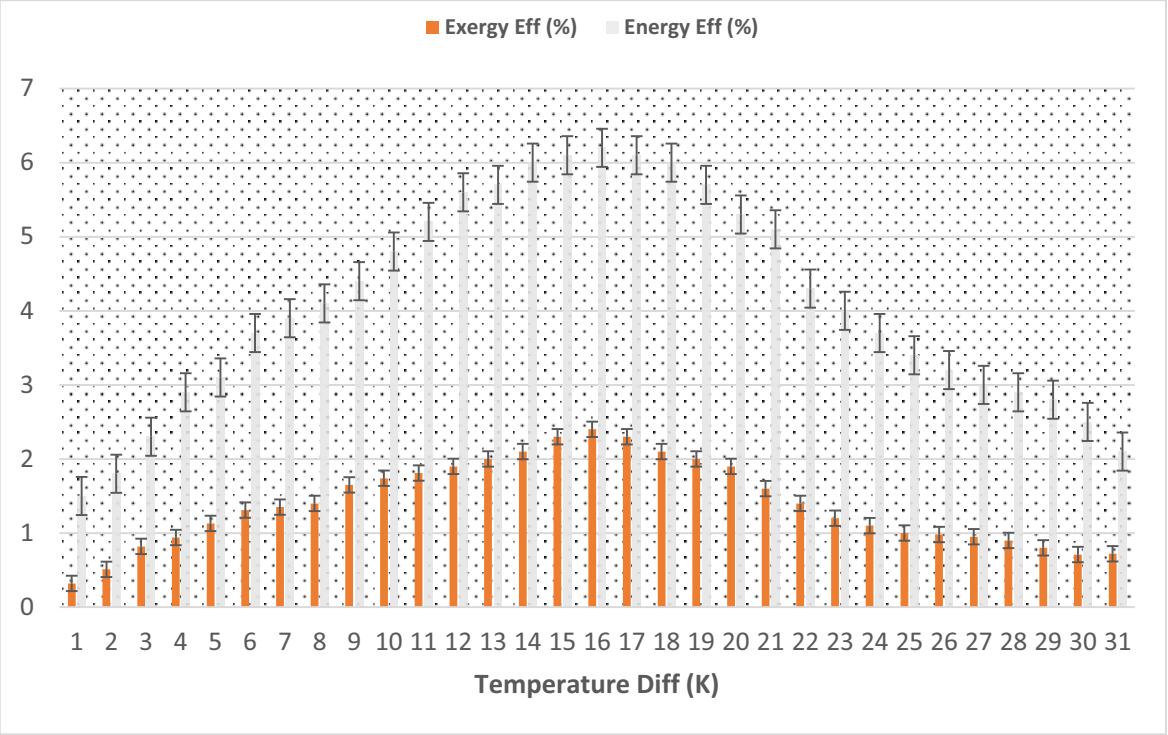


Figure 18. Effect of Temperature Difference on Energy and Exergy Efficiency of Solar Box

The exergy and energy efficiency of the solar box cooker during sensible heating of 2 litres of water in November 2018 and January 2019 is shown in Figures 19 and 20. Again, the variations in the results were due to the unstable weather condition, poor and cloudy sky. The increase in entropy and irreversibility of the cooker and its surroundings caused a reduction in the exergy efficiency of the cooker [40]. The thermal inertial effect and the empty space minimization are what causes this irreversibility [41], [25]. The reduction in energy efficiency was a result of the variations in some atmospheric conditions such as the turbidity, the total amount of water vapour in the air and an increase in significant levels of cloud cover [25].

It was also deduced that the exergy efficiency was lower than that of the energy efficiency majorly as a result of large exergy of the escaping insolation and also due to the deterioration of the insolation absorber on the surfaces of the cooking pot and the reflector.

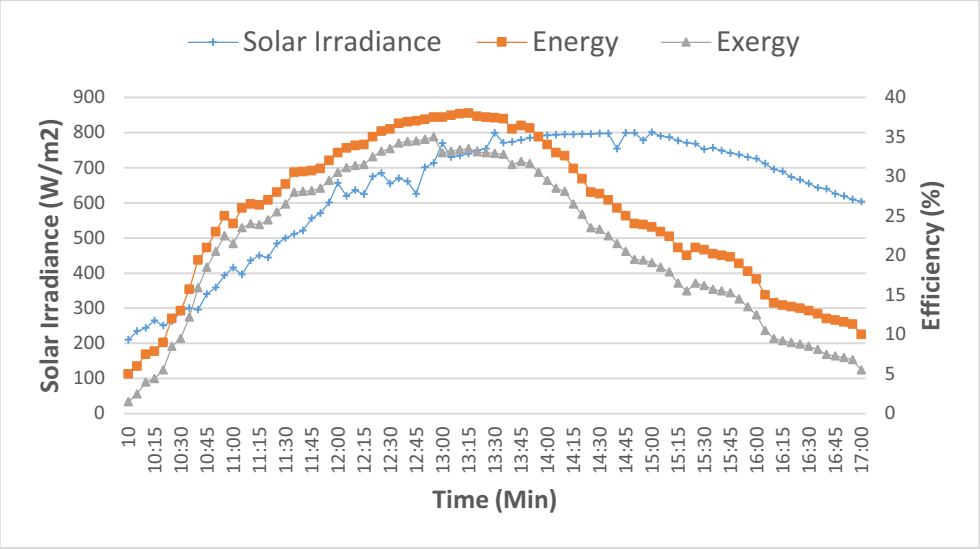


Figure 19. Average Energy and Exergy Efficiency against Time of Box Cooker in the Month of November 2018

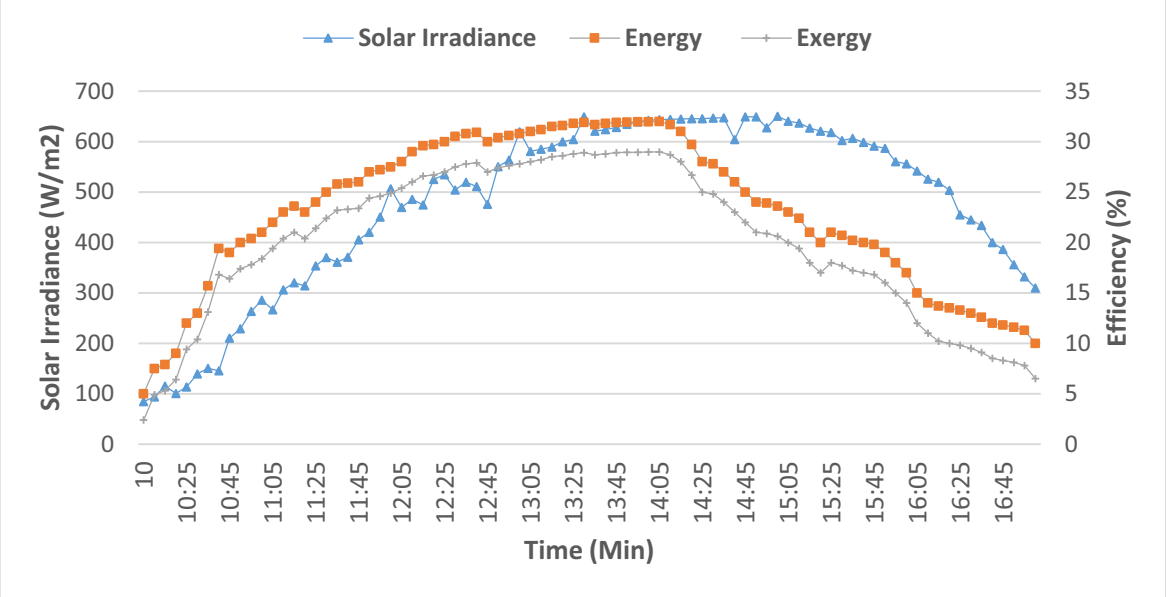


Figure 20. Average Energy and Exergy Efficiency against Time of Box Cooker in the Month of January 2019

Figure 21 and 22 show the result that solar box installed in Omu-Aran even in random weather can sustain a ratio of water to absorber temperature above 0.80 during the pre-boiling heating process means that the cookers can be recommended for use in sterilization.

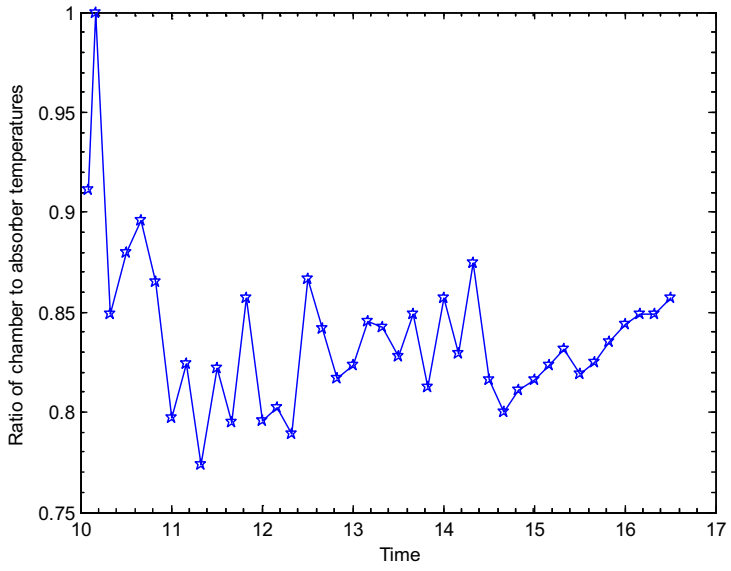


Figure 21 Ratio of the chamber to absorber temperatures

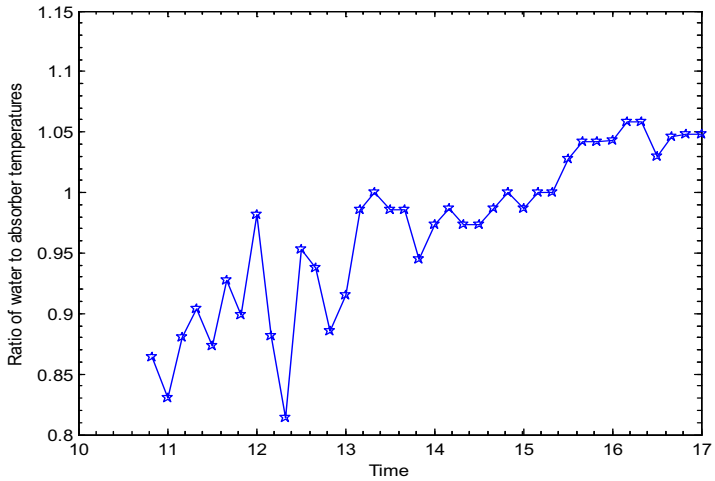


Figure 22 Ratio of water to absorber temperatures

Conclusion

A solar box cooker was produced using locally sourced materials to reduce dependence on fossil fuel and eliminate its negative effects on the environment. Stagnation and sensible tests were carried out in Landmark University, Omu-Aran, Kwara State from January 2018 to January 2019. The ASHRAE empirical model was used to predict the solar irradiance in Omu-Aran metropolis. The average exergy and energy efficiency of the cooker where 28^{o}C and 32^{o}C respectively. The energy efficiency was always greater than the exergy efficiency as a result of the reduction of absorber insolation on the surfaces of the cooking pot and the plane reflector. The fluctuation of energy and exergy efficiency were as a result of turbidity, a variation of solar irradiance and myth of over-cask sky. The ratio of the chamber to absorber temperatures was always above 0.75 and on a sunny day, the cooker absorber was observed to attain higher temperatures than 126.5 ^{o}C. The cooker can be used as a solar oven for roasting and cooking purposes. Also, the heated water in the pot can retain a higher temperature than that of the absorber during the cooling process. This means that the period of sterilization can be elongated in the cooker.

Acknowledgements

The authors wish to acknowledge the financial support offered by Landmark University in the actualization of this research work for publication

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