ARID ZONE JOURNAL OF ENGINEERING, TECHNOLOGY & ENVIRONMENT
AZOJETE December 2020. Vol. 16(4):773-784
Published by the Faculty of Engineering, University of Maiduguri, Maiduguri, Nigeria.
Print ISSN: 1596-2490, Electronic ISSN: 2545-5818
www.azojete.com.ng

ORIGINAL RESEARCH ARTICLE

PERFORMANCE EVALUATION OF SOLAR OVEN USING KAPOK WOOL AS INSULATION MATERIAL

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ARTICLE INFORMATION

Submitted 2 July, 2019
Revised 26 October, 2020
Accepted 8 November, 2020.

Keywords:
Solar oven
Insulation materials
Kapok wool
Stagnation temperature
Efficiency

ABSTRACT

Solar ovens are among common devices which utilize insulation materials because of their ability to retards heat transfer by acting as barriers in the path of heat flow. Previous solar box cookers have used cotton, saw dust, and fibre-glass as insulation materials but none has used Kapok wool despite its potential. This study is aimed at the performance evaluation of solar oven using Kapok wool as the insulation material. The solar box oven designed is of the size 59 x 56 x 36cm dimensions made of plywood, with an aperture area of 3304cm^2 double glass cover and an oven's floor area of 1225cm^2 made of aluminum. Kapok wool was used to line the oven's walls and floor serving as insulator. The solar box oven was tested at the University of Maiduguri, Borno State, Nigeria. It was tested without load to determine its stagnation temperature and to check its endurance under stagnation conditions. Similarly, a water boiling test was conducted to cook rice and beans. The results show that maximum stagnation temperature was 165.1°C and maximum overall daily thermal efficiency of 19.44% was achieved on a clear day test without reflector. The field test of the solar oven demonstrated its ability to cook rice and beans well with 1 kg of rice cooked under 2 hours, while 1 kg of beans was cooked under 1 hour 45 minutes on the same day. This performance demonstrated the suitability of Kapok wool as insulation material for solar ovens.

1.0 Introduction

The use of Solar thermal devices such as solar box oven and solar brick oven are on in the increase because they offered no fuel cost, environmentally friendly, easily operable among other advantages. The basic concept of solar oven is simply to trap and store solar energy inside a box. The box's upper side is covered by a transparent material and well-insulated with a reflector at the top which could be used to boosts the incident energy and also functions as an outer cover when the oven is not in use (Sayigh, 1977; Suharta, 1994; Mukherjee and Chakrabarti, 2004). The challenges of producing reliable and competitively economic solar box for household purposes have led to intense research work in all areas of improving component parts of a solar box cooker (Suharta et al., 1998; Abdulrahim et al., 2015; Maina et al., 2016; Qandil et al., 2018).

Solar Box oven is among common devices which utilize insulation for lagging. Thermal insulations play a major role in the design and production of energy efficient process, devices and systems because of their ability to retards heat transfer by acting as barriers in the path of heat flow. Previous solar box cookers have used Cotton, Saw dust, and Fibre-glass as insulation materials (Suharta et al., 1998; Abdulrahim et al., 2015; Adewole et al., 2015; Maina et al., 2016; Adewumi et al., 2019). Cotton is widely used in cloth making and, in the hospital, while saw dust is used in stove for cooking as well as in making furniture products which could reduce their availability. Fibre-glass is a synthetic fiber with high toxin ratings and usually imported into the country. Natural fibers which have low to zero toxin ratings, easy to reuse and dispose with significant health benefits have been recognized as possible alternative. Possible material for replacing these insulation materials was conceived, and the locally available insulating materials that have been considered in this study is Kapok wool. Kapok is a natural polymer and it is a unicellular fibres like cotton with a thermal conductivity of $0.035Wm^{-1}K^{-1}$ (Ayugi, 2011). Voumbo et al. (2010) study shows that the kapok's conductivity dregs between 0.03 and 0.04 W/m.°K for density between 5 and 40 kg/m^3, and taking into account year average diffusivity of 17.1x10G7 m^2/s, they concluded that kapok is a good heat insulator.

Typical analyses indicate that Kapok fibers comprises of 64% cellulose ($(C_6H_{10}O_5)_n$), 13% lignin and 23% pentosan (Chalarrekij et al., 2011). Besides these constituents, they also contain wax cutin on the fiber surface which makes them water repellent (Chalarrekij et al., 2011).

Purnawati et al. (2018) described kapok fibers as having a hollow structure with a thin fiber wall and a large lumen filled with air which led to low fiber density, and that hydrophobic properties are associated with the wax content of the fiber surface. Meiwu et al. (2010) and Mwaikambo (2006) stated that kapok was the lightest fiber in the world. Studies have also confirmed that kapok fibers have excellent thermal and acoustic insulating properties, high buoyancy, and good absorbency for oil and other non-polar liquids distinguishing kapok from most other cellulosic fibers (Wang et al., 2012; Lim and Huang, 2007; Zheng et al., 2015).

Purnawati et al. (2018) have explained that there are three types of weight/mass loss during thermal degradation: water removal (drying), organic matter release (devolatilization), and bonded-carbon oxidation (slow combustion). In thermal degradation, the first aspect is water desorption in the temperature range of 29.9°C–65.1°C for kapok fiber and it is endothermic. The second and third peaks are exothermic, and they occurred at 322.8°C and 444.1°C respectively for kapok fiber. The third peak expressed the final decomposition of cellulose as well as lignin degradation. Gaan et al. (2009) also identified three stages of cellulose thermal decomposition. The first stage occurred at a temperature of 100°C and represented the release of water. The second stage, at a temperature of 360°C, was identified as a rapid dehydration and decarboxylation reaction that produced combustible gases such as aldehydes, ketones and ethers. The third stage, at 400°C, was classified as the second stage of decomposition and charcoal formation. Lignin degradation occurred at a temperature of 250°C–500°C because of its high stability which made it difficult to decompose (Poletto et al., 2012).

While a great deal has been published about solar box ovens or solar box cookers that use other materials as insulators, there is hardly any mention of one using kapok wool as insulator. The reason is not that kapok wool is not a good insulator, but they are unexplored. Hence, this study would conduct a performance evaluation of solar oven using Kapok wool as an insulation material.

2. Materials and Method

2.1 Materials

The design concept adopted for the solar oven following Suharta et al. (1998). The constructed Solar box oven consisted of four components, namely box made of wood, absorber plate made of Aluminum sheet which was painted black at its upper surface and Kapok wool was used as the insulator. The solar box oven is of the size 59 x 56 x 36cm dimensions with an aperture area of $3304cm^2$ and absorber plate made of Aluminum sheet of 0.4mm thick with an oven's floor area of $1225cm^2$, while its total surface area was 5134.6 cm^2 and a height of 19cm as shown in Figure 1. Kapok wool was used to line the oven's walls and floor. Kapok pod was obtained at the University of Maiduguri, Maiduguri, Nigeria from Kapok Trees (Figure 2a). The

Kapok wool was removed from its pod and hand picking of the kapok seed in the Kapok wool was done and the Kapok wool was then brushed to remove other unwanted particles (Figure 2b).

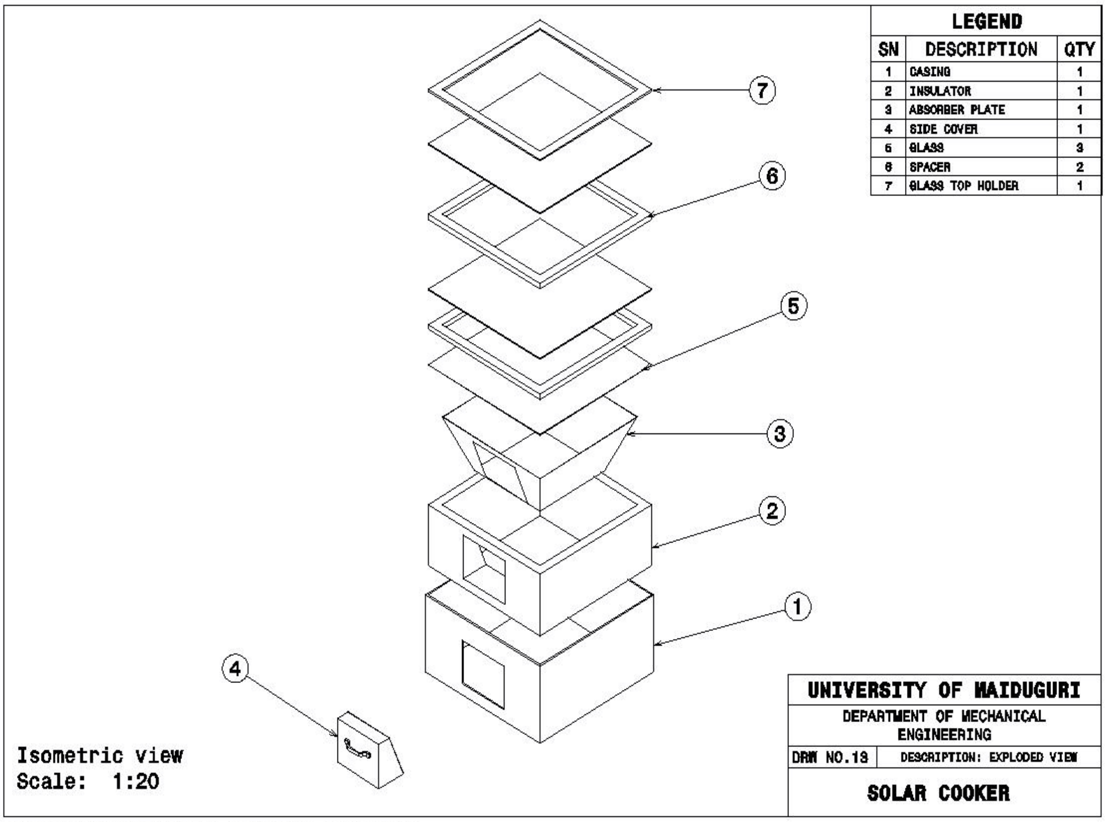

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Figure 1: Exploded View of Solar box oven.

(a) (b)

Figure 2: Kapok Source and Processing: (a) Kapok Pod; (b) Kapok Wool, Seed, Exocarp and Other unwanted particles

The Top view of the solar box oven is shown in Figure 3a. The Kapok wool of average thickness of 100mm was put at the sides of the absorber plate and kapok wool of thickness 40mm at the bottom of the absorber plate. Kapok wool was also put inside the solar box oven entrance cover to serve as insulation material as shown in Figure 3b, c, d. A total mass of 2.026 kg of kapok wool was used to cover a total volume of 0.0469 m^3.

(a) Top view of Solar box oven

(b) Bottom view of Solar box oven

(c) Solar box filed Kapok insulator

(d) Solar box's door cover filled with Kapok

Figure 3: Solar Box Oven stuffed with Kapok wool as insulation (a, b, c and d)

Thermometer data recorder (3 Channels, Model: MTM-380SD, accuracy 0.1°C) was used to monitor the temperature profiles in the oven's floor (absorber plate) and water temperature. The Solar Power Meter (Model: SPM-1116SD, accuracy 0.1W/m^2) was used for measuring Solar Insolation while Aerometer (Model: ABH-4224, accuracy 0.1m/s) was used to measure the Wind speed and Ambient temperature.

2.2 Method

The solar box oven as shown in Figure 4 was tested at the Entrepreneurship Centre, University of Maiduguri, Borno State Nigeria without a load to determine its stagnation temperature and to check the oven endurance under stagnation conditions. Water boiling test and cooking of rice and beans was also carried out using the solar oven. The solar oven is preheated for 30 minutes using solar energy to remove vapor inside the oven which can limit the rate of the cooking performance. Then, the loading test was done by placing the cylindrical pot covered with a lid filled with 1 litre of water inside the solar box oven. And for cooking food, the food items were put inside the cylindrical pot covered with a lid filled with water inside the solar box oven. Thermometer data recorder (3 Channels, Model: MTM-380SD, accuracy 0.1°C) was used to monitor the temperature profiles in the oven's floor (absorber plate) and water temperature. The Solar Insolation was measured using Solar Power Meter (Model: SPM-1116SD, accuracy 0.1W/m^2) while the Wind speed and Ambient temperature (T_4) were measured using Aerometer (Model: ABH-4224, accuracy 0.1m/s). Figure 4 shows the Solar Box Oven under test.

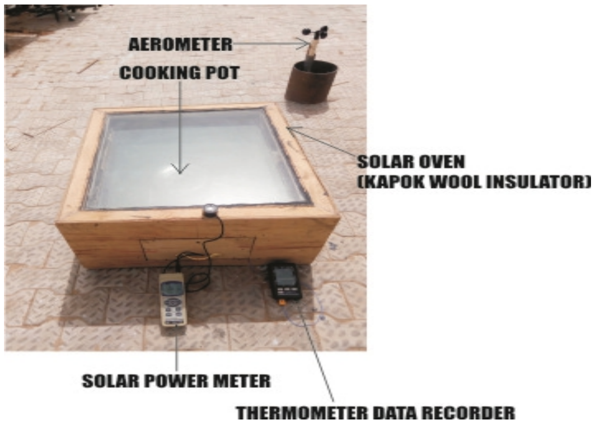

Figure 4: Solar box oven under Test

Performance Tests were repeated on the same Solar oven, and the performance evaluation carried out were: i. Stagnation temperature, and ii. Solar box oven Efficiency.

The overall thermal efficiency of the solar box oven is expressed mathematically by Khalifa et al. (2005) and Olwi et al. (1993) as reported in El-Sebaii and Ibrahim (2005) as:

$$\eta_u = \frac{M_w C_w}{I_{av} A_c} \frac{\Delta T}{\Delta t} \qquad (1)$$

Where η_u represents the overall thermal efficiency of the solar box oven, M_w mass of water (kg), C_w specific heat capacity of water (J/kg°C), ΔT temperature difference between the maximum of the cooking fluid and the ambient air temperature, A_c the aperture area (m^2) of the oven, Δt time required to achieve the maximum temperature of the cooking fluid, I_{av} the average solar radiation intensity (W/m^2) during time interval Δt.

3.0 Results and Discussion

3.1 Preliminary Test

The results of the stagnation test of the solar oven at no load is shown in Figure 5, and the maximum temperature attained was 148.3°C at 13:00 hours (1:00pm). This is due to the fact that on a clear sunshine the solar energy increase to a maximum at solar noon and the solar collector received this energy and its distribution within the solar box is a function of time. Maximum wind speed recorded was 1.7m/s which has not exceeded 2.5m/s for which the data shall be discarded if such value lasted for more than 10 minutes (ASAE S580.1, 2013).

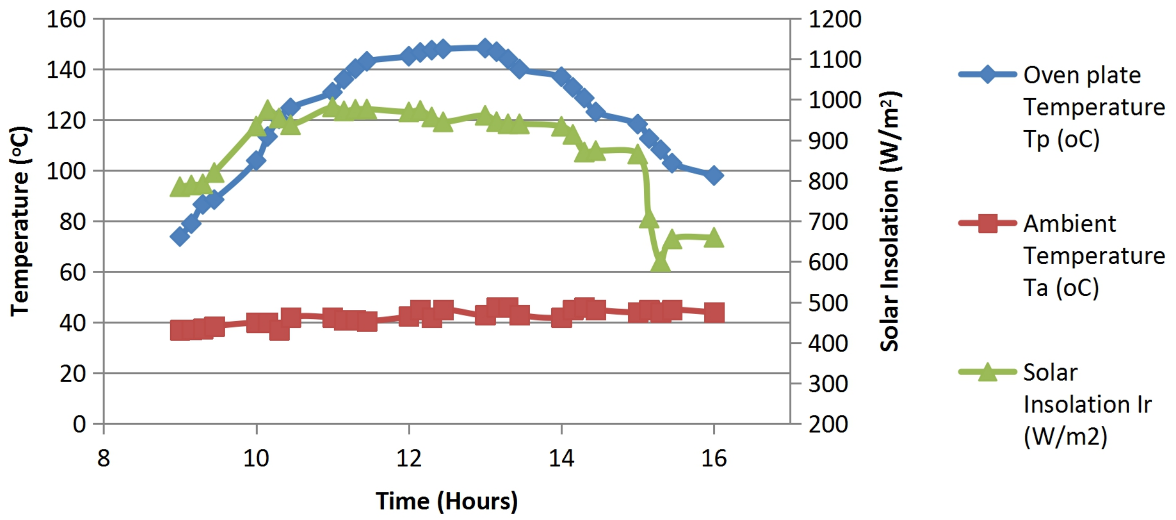

Figure 5: Stagnation Test of Solar Oven at no-load at University of Maiduguri, Maiduguri, Nigeria.

The results of 1 litre of water boiling test using the solar oven is shown in Figure 6. The water temperature reached a maximum of 99.8°C at 12:00 noon. This could be regarded as the boiling temperature of the water, and since most food can be fully cooked at the temperature range of 60 - 90°C the solar oven performance is good and suitable for cooking. The overall daily efficiency of the solar oven (η) was calculated using equation (1) to be 11.6% where M_w = 1kg, C_w = 4220 J/(kg.K), A_c=0.3304m², I_{av} = 857.28W/m², ΔT=55.86°C, and Δt=7200s.

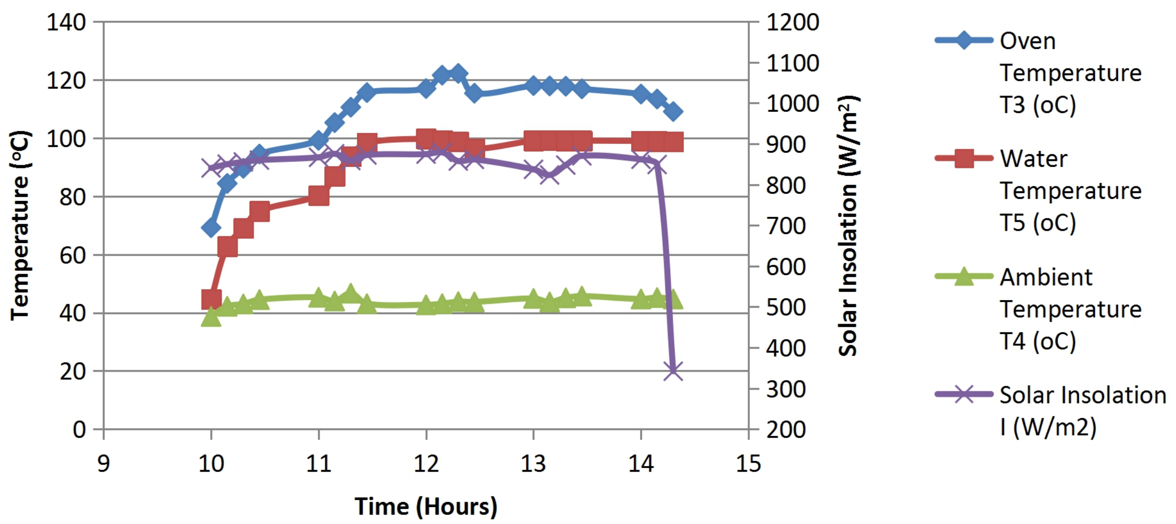

Figure 6: Solar box oven Water Boiling Test (1 Litre of Water) at University of Maiduguri, Maiduguri, Nigeria.

Tables 1 and 2 show the results obtained when the solar oven was used to cook 1 kg of rice and beans each where cooking times, oven plate temperatures and ambient conditions of temperature and solar insolation were noted. Rice was cooked under 2 hours after placed inside the oven, and Beans was cooked under 1 hour and 45 minutes after placed inside the oven.

Table 1: Cooking Test using Rice as food item

Time (s)	Oven plate Temperature T_p (°C)	Ambient Temperature T_a (°C)	Solar Insolation I (W/m^2)	Wind Speed V (m/s)
9:30	72.2	39.0	912.5	0.5
9:45	79.4	41.2	924.5	0.2
10:00	86.8	40.6	937.6	0.1
10:15	93.8	40.1	930.6	0.0
10:30	100.4	40.8	952.5	0.0
10:45	106.6	41.9	948.0	0.0
11:00	108.5	43.1	943.4	0.0
11:15	114.4	42.5	948.8	0.0
11:30	119.2	43.2	961.5	0.0

Rice cooked as at 11:30 am

Table 2: Cooking Test using Beans as food item

Time (s)	Oven Temperature T_p (°C)	Ambient Temperature T_a (°C)	Solar Insolation I (W/m^2)	Wind Speed V (m/s)
12:00	106.7	46.0	925.1	0.1
12:15	104.9	46.9	930.3	0.0
12:30	109.0	47.3	932.0	0.0
12:45	114.0	43.9	961.5	0.0
1:00	117.0	46.3	949.7	0.0
1:15	119.2	46.8	941.5	0.0
1:30	119.2	45.8	935.2	0.0
1:45	118.8	49.0	970.6	0.0

Beans cooked as at 1:45 pm

3.2 Stagnation Temperature Tests

During the repeated tests carried, Temperatures of the absorber plate of the oven during the day having fluctuating insolation is shown in Figure 7. The plots of Oven plate temperature (T_p), Ambient temperature (T_a) and Solar Insolation (IR) indicate that the Solar insolation recorded a minimum of 409.5 W/m^2 at 10:15 am and a maximum of 963.6 W/m^2 at 11:10am. The maximum absorber plate temperature obtained was 151.1°C recorded at 12:55pm, the temperature between the Absorber plate and the ambient temperatures was 109.1°C at 12:55pm, while the maximum Ambient air temperature is 44.3°C. Maximum wind speed recorded was 1.9m/s which has not exceeded 2.5m/s for which the data shall be discarded if such value lasted for more than 10 minutes (ASAE S580.1, 2013). These results have demonstrated the suitability of the solar oven for heating water and cooking even during fluctuated weather condition.

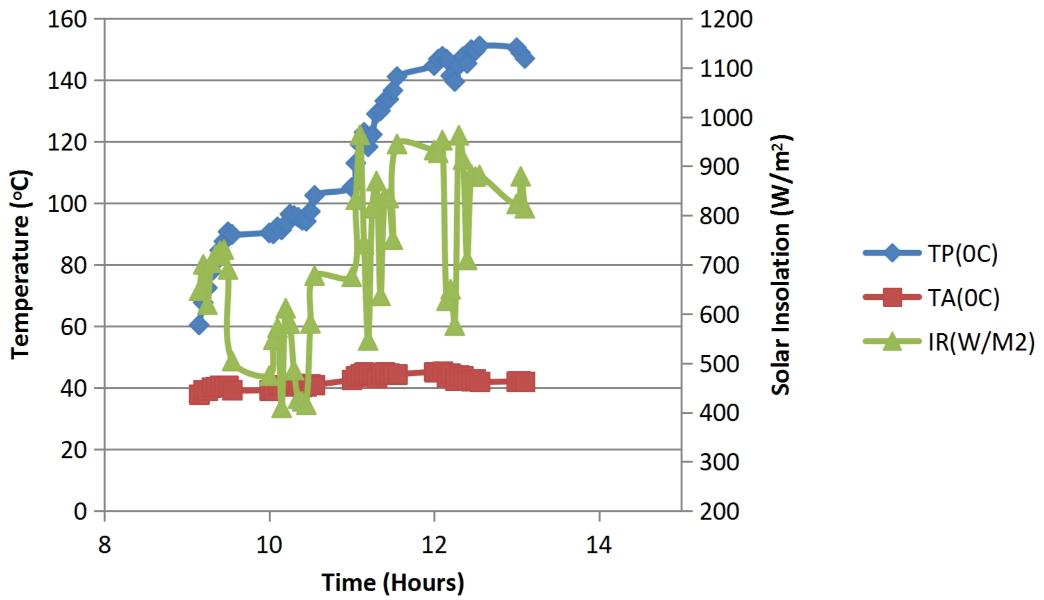

Figure 7: Stagnation Test (Fluctuation Insolation) at University of Maiduguri, Maiduguri, Nigeria. (TP = Oven Plate Temperature, TA = Ambient Temperature, IR = Solar Insolation).

Also, the temperature distribution inside the oven during clear weather day (14/04/2020) is shown in Figure 8. The plots of TP, TA, and IR indicate that the Solar insolation (IR) reached a maximum of 1056 W/m^2 at 11.35am while the maximum absorber plate temperature (Tp) attained was 165.1°C at 12:10pm and maximum ambient temperature (TA) recorded was 46.3°C at 13:05pm. The temperature between the Oven plate and the Ambient Temperature was 123.7°C at 12:10pm.

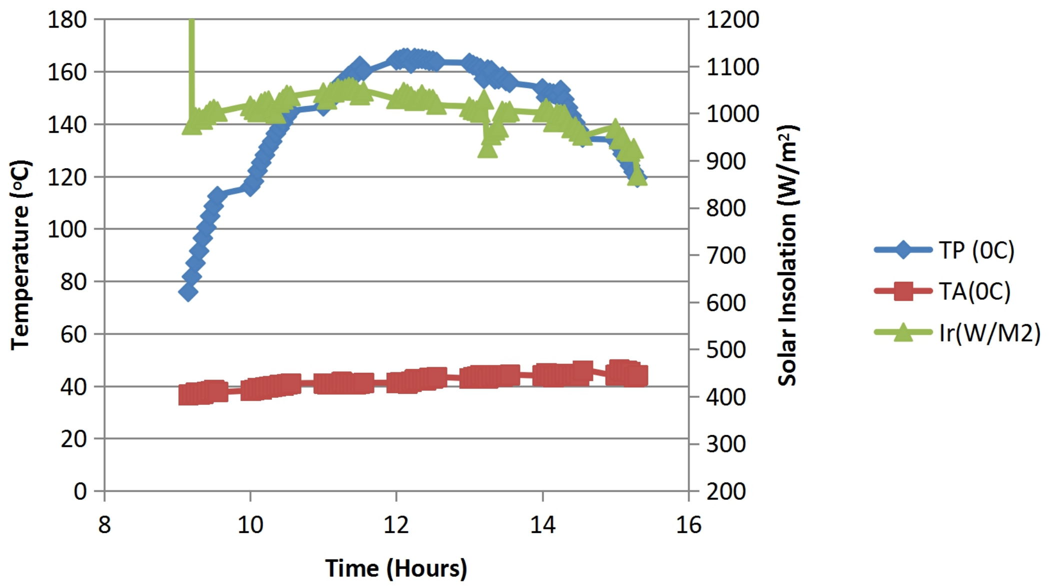

Figure 8: Stagnation Test (Clear Weather Condition) at University of Maiduguri, Maiduguri, Nigeria. (TP = Oven Plate Temperature, TA = Ambient Temperature, IR = Solar Insolation).

The oven reached a maximum temperature of 151.1°C on the day of fluctuating insolation, and a maximum oven temperature of 165.1°C on the clear weather day. The temperature attained on a clear weather day is higher than the corresponding temperature on fluctuating insolation day by 14°C. This is because at any moment clouds intercept the sun, it decreases the energy to a low value due to the diffuse sky radiation (Sayigh, 1977). Earlier studies have reported difference levels of solar ovens (cookers) performances with respect to stagnation temperatures attained. These include, Suharta et al. (1998) who reported that one of their solar ovens with reflector reached 183°C while another one attained a temperature of 202°C. And Adewumi et al. (2019) also reported that their solar cooker with no reflector attained a temperature of 69.8°C while the one with four reflectors attained a temperature of 175°C. In the case of Adewole et al. (2015), the stagnation temperature attained by their solar cooker with reflectors was 76°C. Though there are those solar ovens with higher stagnation temperatures than that of the present study as reported, it could be observed that such solar cookers were installed with reflectors which boosts the incident energy thereby increasing the heat energy available to the absorber plate. The maximum stagnation temperature of 165.1°C attained in this study could cook most foods fully because temperature range of 60-90°C is required to cook any food (Folaranmi, 2013), and the oven endurance under stagnation conditions has also been confirmed.

3.3 Start cook time

Suharta et al. (1998) defined a 'start cook point' as time for a standard load of 1.2 l of water to reach 80°C. Since water has a higher specific heat than any food, it provides the heaviest load for the performance test. The boiling test results are presented in figure 6. The temperature of the water heated in the oven reached 80°C at 10:31am. The performance was quite similar to the performance of the one reported by Suharta et al. (1998) in which the solar oven attained 80°C at 10:25am though his own uses one reflector. It has been reported by Suharta et al. (1998) that Users can generally start cooking 1 h before the 'start cook point', and for this oven, at 9:31am.

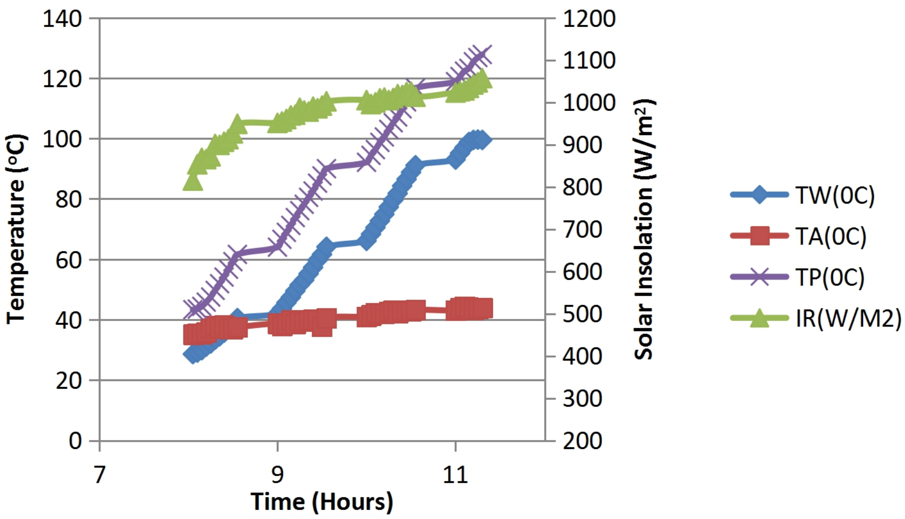

Figure 9: Boiling Test on a Clear Weather Condition at University of Maiduguri, Maiduguri, Nigeria. (TW = Water Temperature, TP = Oven Plate Temperature, TA = Ambient Temperature, IR = Solar Insolation).

The results of 1.2kg of water boiling test using the solar oven on 15th April, 2020 is shown in Figure 9. The water temperature reached a maximum of 99.6°C at 11:25am. The overall daily efficiency of the solar oven (η) was calculated using equation (1) to be 9.6% where M_w=1.2kg, C_w = 4220 J/(kg.K), A_c = 0.3304m², I_{av} = 971.22W/m², ΔT=58.6°C, and Δt = 9600s.

The results of 2.643kg of water boiling test using the solar oven on 16th April, 2020 is shown in Figure 10. The water temperature reached a maximum of 99.6°C at 1:00pm. The overall daily efficiency of the solar oven (η) was calculated using equation (1) to be 18.8% where M_w = 2.643kg, C_w = 4220 J/(kg.K), A_c = 0.3304m², I_{av}=1031.52W/m², ΔT = 55.22°C, and Δt = 9600s.

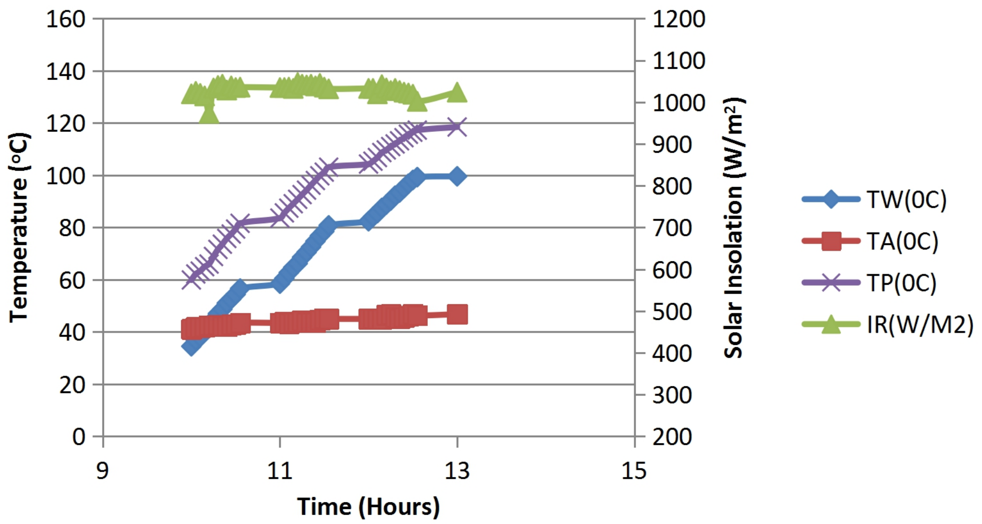

Figure 10: Boiling Test of 2.643 litres of Water on Clear Weather Condition at University of Maiduguri, Maiduguri, Nigeria. (TW = Water Temperature, TP = Oven Plate Temperature, TA = Ambient Temperature, IR= Solar Insolation)

The results of 2.313kg of water boiling test using the solar oven on 17th April, 2020 is shown in Figure 11. The water temperature reached a maximum of 99.1°C at 12:10pm. The overall daily efficiency of the solar oven (η) was calculated using equation (1) to be 19.44% where M_w = 2.312kg, C_w = 4220 J/(kg.K), A_c = 0.3304m^2, I_{av}=1076.14W/m^2, ΔT=55.26°C, and Δt = 7800s.

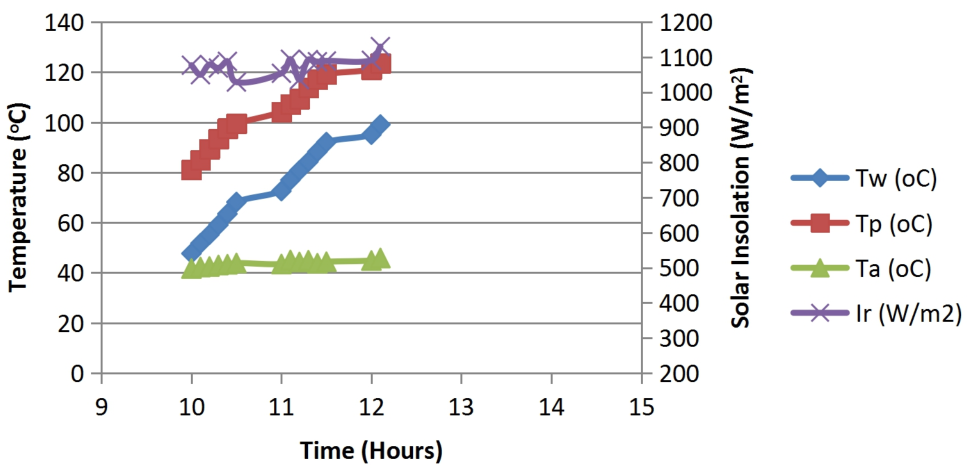

Figure 11: Water Boiling Test of 2.313kg of Water on a Clear Weather Condition at University of Maiduguri, Maiduguri, Nigeria.

The maximum overall daily efficiency obtained during the various tests carried out was 19.44% and it is an indication of good performance and better heat retention ability of the cooker since the solar oven is without reflector. Though solar thermal efficiency of 33% have been reported by Adewole et al. (2015) based on performance of a reflected solar box cooker implemented in Ile-Ife, Nigeria, Adewumi et al. (2019) reported the performance of solar cookers tested at Ilorin, Nigeria and confirmed that the efficiency of the solar cookers increases with increase number of reflectors from 18.72% (no reflector) to 72.22% (four reflectors). All these reported cases above used reflectors, so if one or more reflectors are introduced to the solar oven in this study, there will be increase in thermal efficiency.

4.0 Conclusion

The use of loose Kapok wool as insulation material in solar oven has been evaluated in this study. The results based on the performance evaluation carried out in Maiduguri, Nigeria show that it can serve as a good insulator. The use of Kapok wool has ensured insulation and increases oven temperature. The maximum stagnation temperatures obtained were 151.1°C on day of fluctuating insolation and 165.1°C on clear weather day. Maximum overall daily thermal efficiency of 19.44% was obtained on a clear day test without reflector. The field test of the solar oven has also demonstrated its ability to cook rice and beans well. For example, 1 kg rice was cooked between 9:30 and 11:30am while 1 kg beans cooked between 12:00 noon and 1:45pm. The solar oven performance has demonstrated the suitability of Kapok wool as insulation material for solar ovens and it is here by recommended for use for this purpose.

Acknowledgements

The authors would like to acknowledge the TETFund through the IBR Research Grant No. TETFUND/DESS/UNIMAID/MAIDUGURI/RP/VOL.II at University of Maiduguri, Maiduguri, Nigeria for providing financial support for the study.

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