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ORIGINAL RESEARCH ARTICLE

ASSESSMENT OF SOLAR BOX COOKER (SBC) WITH KAPOK FIBER INSULATOR UNDER MAIDUGURI WEATHER CONDITIONS

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ABSTRACT

This paper presents the construction and performance evaluation of solar box cooker with kapok insulator. The solar cooker offers an economically viable alternative while mitigating environment degradation due to excessive use of biomass/conventional energy sources for cooking purposes. The Bureau of Indian Standard (BIS: IS B429) was used to determine the thermal performance parameters of the cooker, where first figure of merit (F1) and second figure of merit (F2) were determined to be F1= 0.132 and F2= 0.58. The cooker thermal efficiency (η) = 44%, qualifying the cooker to be grade "A" according to BIS. The American Society of Agricultural and Biological Engineers for Solar Cooking (ASAE S580.1) was used to determine the cookers cooking power and it was found to be (Ps) =14.7W while the (R2) value was 0.137 coefficient of regression

1.0 Introduction

In developing countries, access to energy is one of the major problems confronting them, a considerable proportion of rural and urban dwellers in the Nigerian population as in many other developing countries in Africa rely on fossil fuels, biomass and fire wood cooking and domestic water heating. Burning of fossil fuels has been identified to create two adverse effects on our environment; (i) it produces greenhouse gas (GHG) emissions that cause global warming, and (ii) the by-products of burning, such as sulphur dioxide, soot, and ash that are responsible for global dimming by changing the properties of the cloud (Akorede, *et al.,* 2017). Owing to these adverse effects there is urgent need to conserve our environment from these pollutants leading to a global search for alternative clean energy sources. Nigeria is blessed with an abundant amount of sunshine which has been estimated to be 3,000 hours of annual sunshine (Bello *et al.,* 2010). From the average amount of solar energy reaching the country, it is evident that the development of Solar technology will be worthwhile. Maiduguri Metropolitan Council (MMC) shares local boundaries with Konduga, Jere and Mafa local government areas (LGAs) and it has an area land mass of 300 square kilometers (300 km^2), which lies between latitude 12° N to 13° N and longitude 13° E to 15° E respectively. The vegetation is of semi – arid zone and climatic condition in this area is of a hot dry season (27°C to 42°C), and an annual rainfall of 500 mm to 600 mm has been recorded (Mohammed *et al.*, 2017). Fortunately, Maiduguri possesses ample amount of solar radiation sunshine hours and this offers solar cooking as one of the most attractive options.

For testing the performance of box solar cookers, Mohammed *et al.* (2013), carried out performance testing of a truncated pyramid solar thermal cooker this design geometry concentrates the incident solar energy radiations towards the absorber placed at the bottom, it improves the performance of the solar cooker. Garbaand Dan-mallam (2014) undertook a Comparative performance tests of a painted and non-painted cooking pot where the result shows the painted pot heat gains was 22% compared to the non-painted cooking pot. Elamin and Abdallah (2015), carried out a research on Design, Construction and Performance Evaluation of Solar Cookers, results of thermal performance showed that the parabolic solar cooker attained a maximum temperature of 86.5°C on average basis and was the best followed by the box-type solar cooker that attained a maximum temperature 52.36 °C and finally the panel-type that attained a maximum temperature of 43.5°C. Also the results of the solar cookers efficiency for the parabolic cooker, box-type and panel-type were found to be 31.53%, 77.4% and 67.4%, respectively. Ademola and Joseph (2015) studied energetic and exergetic evaluation of box-type solar cookers using different insulation materials insulated like maize cob, air (control), maize husk, coconut coir and polyurethane foam respectively were observed over a period of three years. The energy and exergy efficiency were highest in the cooker with coconut coir (37.35 and 3.90% respectively) in the first year but was lowest for air (11 and 1.07% respectively) in the third year. These results reiterate the importance of a good insulating material for a box-type solar cooker. Abdoulkader *et al*., (2017) on their study of the Thermal Performance Testing and promotion of solar cooker under Djiboutian climate. It was found that solar cooker was of A grade. The experimental results obtained for thermal performance showed that the solar cooker is capable of cooking variety of foods easily under Djiboutian climate. Ramesh *et al.* (2018), in the study of the performance evaluation and cost economics of developed box type solar cooker observed that two figure of merits (F_1, and F_2), standard cooking power (P_s)and thermal efficiency of solar cooker were 0.1084, 0.31, 58.41 watt, and 37.76% respectively.

Mullick et al. (1987) carried out thermal evaluation of box type solar cookers and proposed suitable thermal tests and also identified appropriate parameters, which pertain to the solar cooker and are relatively independent of the climatic variables as well as the products cooked. Box type solar cookers are suitable mainly for the boiling type of cooking. A large fraction of the mass of most of the food products are due to water, hence, the cooking temperature is close to 100˚C. Mullick et al. (1987) in evaluating the box type solar cooker identified cooking parameters as first figure of merit $F_1$and second figure of merit F_2, which are independent of climatic variables. In the procedure proposed by Mullick et al. (1987), the first test is a stagnation test without load and the first figure of merit (F_1) is obtained. The second test involves sensible heating of a full load of water in container and from this; second figure of merit (F_2) is obtained. Funk, (2000) ASAE S580.1 standard, the goal of this standard was to produce a simple, yet meaningful and objective measure of cooker performance that was not so complicated as to make testing in less developed areas impracticable. American Society of Agricultural and Biological Engineers for Solar Cooking procedures (ASAE S580.1) monitors the average temperature inside a pot of water while the cooker is operated under a set of guidelines given in the standard for tracking procedure, thermal loading, etc. Temperature measurements are made of the water and averaged over 10 minute intervals. Ambient temperature and normal irradiance (solar energy flux per area) are also measured and recorded, at least as often as load temperature. Under conditions of high wind, low insolation, or low ambient temperature, tests are not conducted. The primary figure of merit used by ASAE S580.1 is the Cooking Power, *P*.

In the present work, a trapezoidal shape solar box cooker with Kapok fibre insulator is been constructed and attempt has been made to test its efficiency, evaluate the performance to determine first figure of merit (F1) and second figure of merit (F2) as adopted by Bureau of Indian Standards (BIS: IS B429), and as well determine the adjusted cooking power (P_{ad}) as recommended by (ASAE S580.1).

2.0 Materials and Method

2.1 Description of the cooker

The system consists of an insulating material (Kapok fibre: a natural polymer with a thermal conductivity of 0.035$Wm^{-1}K^{-1}$ (Aguyi, 2011)) in between the inner and outer casing to minimize heat loss. The casings were made with plywood to further minimize heat loss and to serve as barrier to prevent any environmental effect to the solar cooker. Inside the cooking chamber is an aluminium plate coated with anon-toxic matter black colour to achieve high absorption coefficient. The leakage from the box to the surroundings was also minimized by having a rubber gasket (1.5 mm thick) in between the triple glazed cover (25 mm glazing) and the box. The cooking vessel used in this study was bought from the local market, it is made of Aluminium alloy (18 cm in diameter and 10 cm in height) in a cylindrical dish shape and painted black which allows for high absorption of solar radiation designed to keep cooking, filled with water and equipped with a black cover, was placed into the solar box cooker. The isometric views of the casing and the absorber is shown in figure 1 and figure 2 respectively. The optical design of the cooker uses the concept of concentrating solar energy to achieve high temperatures; to trap the collected energy as is done in solar box cookers, and to retain high temperatures over a considerable period of time as obtained in green houses. Due to the geometry of the design, solar rays impinging on the inner sidewalls were reflected downward, so as to create a region of high temperature at the bottom. In such geometries a higher value of the ratio of aperture area to absorber area leads to higher concentration ratio and hence higher absorber plate temperature.

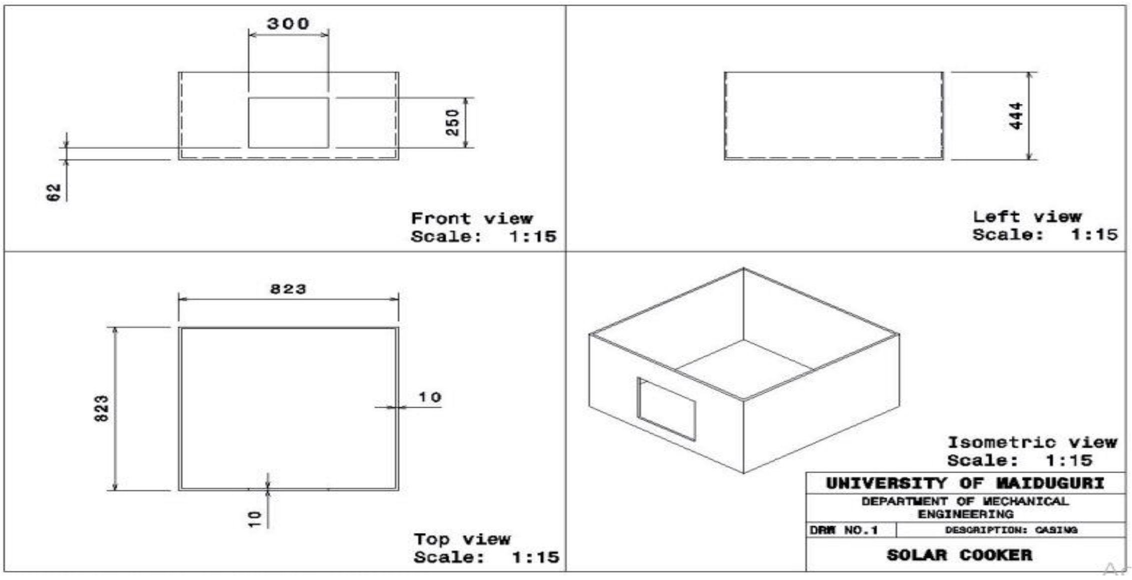

Figure 1: isometric view of solar box casing

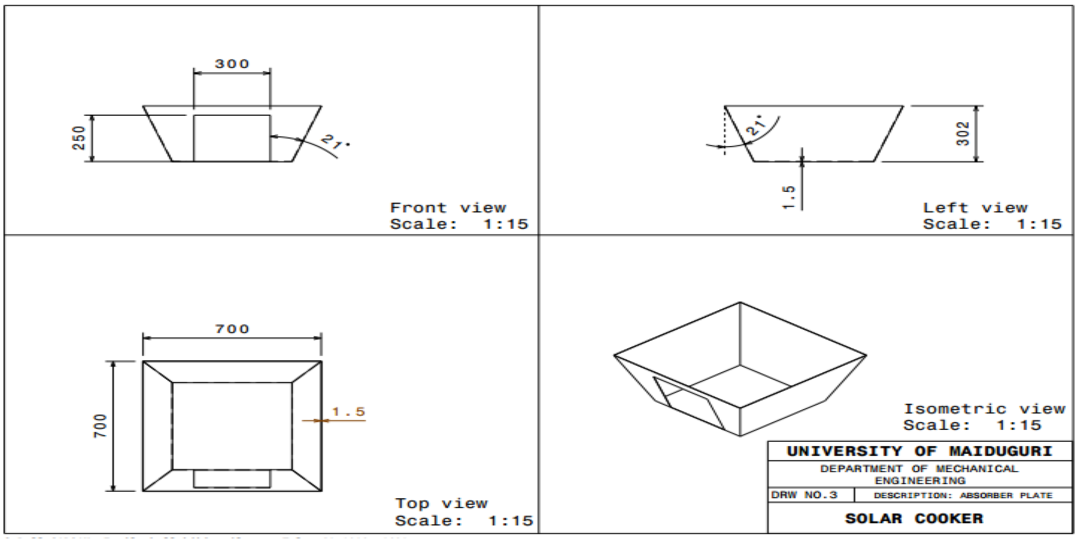

Figure 2: isometric view of solar box absorber plate

2.0Thermal Efficiency

Energy analysis is based on the first law of thermodynamics, i.e. net heat supplied converted into work. Energy analysis thus ignores the reductions in energy potential. This analysis can provide sound management guidance in those applications in which usage effectiveness depends solely on energy quantities. Energy input to the solar cooker is energy of solar radiation per square meter of the solar cooker. Then, energy input to the solar cooker can be calculated as follows; Ozturk. (2004)

$$E_i = I_t \times t \times A_{sc} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

The energy output of the solar cooker can be calculated as follows:

$$E_o = m_w \times C_{pw} \times (T_2 - T_1) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . (2)$$

The energy efficiency of the box type solar cooker with inclined aperture area can be defined as the rat ooker. Energy efficiency of the solar cooker was calculated by using the equation below; Ozturk, (2004)

$$\eta = \frac{E_o}{E_i} = \frac{m_w \times C_{pw} \times (T_2 - T_1)}{I_s \times t \times A_{sc}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . (3)$$

2.1 Performance of solar cooker

The figure of merit $F_1$and F_2 is given for box type solar cooker by Mullick et al. (1987).
First figure of merit F_1 (°C m^2/W) or stagnation testis was given as:

$$F_1 = \frac{T_p - T_a}{I_s} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .. (4)$$

where: T_p, T_a and $I_s$are plate absorber temperature, ambient temperature and solar intensity on a horizontal surface at a time stagnation temperature is reached respectively.
Second figure of merit F_2or water heating test is given as:

$$F_2 = \frac{F_1 (mC_p)_w}{At} \ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w_1} - T_a}{I_s}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w_2} - T_a}{I_s}\right)} \right] \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . (5)$$

where: F_1 is the first figure of merit M_w is the mass of the water, C_w is the specific heat of water, T_{w1} is the initial temperature of water (= 60 °C), T_{w2} is the final temperature of water (= 90 °C), τ is the measured time difference in which the water temperature rises from T_{w1} to T_{w2}, T_a is the average ambient temperature over the time period τ, H is the average solar radiation intensity incident on the aperture of the cooker, and A is the aperture area of the solar cooker.

2.2 Cooking Power

In the year 2000, Funk found a need to evolve Standard for testing solar cookers. The recommendations were later adopted by American Society Agricultural Engineers as (ASAE S580.1).

$$\mathrm{P_i} = (\mathrm{T_2} - \mathrm{T_1})\mathrm{MC_v}/600 \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . \quad (6)$$

where:

P_i= cooking power (W)

T_2 = final water temperature(^{0}C)

T_1 = initial water temperature (^{0}C)

M = water mass (kg)

C_v = heat capacity(4186 J/[kg ·K])

2.2.1 Standardizing cooking power

Cooking power for each interval shall be corrected to a standard insolation of 700 W/m^2 by multiplying the interval observed cooking power by 700 W/m^2 and dividing by the interval average insolation recorded during the corresponding interval.

$$\mathrm{P_s} = \mathrm{P_i}(700/\mathrm{I_i}) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . (7)$$

where:

P_s = standardized cooking power (W)

P_i = interval cooking power (W),

I_i = interval average solar insolation (W/m^2)

multiplying observed cooking power by 700 W/m^2 and dividing by the interval average insolation recorded during the corresponding interval.

2.2.2 Temperature difference

Ambient temperature for each interval is to be subtracted from the average cooking vessel contents temperature for each corresponding interval.

$$\mathrm{T_d} = \mathrm{T_w} - \mathrm{T_a} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .. \quad (8)$$

T_d = temperature difference (^{0}C)

T_w = water temperature (^{0}C)

T_a = ambient air temperature (^{0}C)

2.2.3 Plotting

The standardized cooking power, P_s, (W) is plotted against the temperature difference, T_d, (°C) for each time interval.

2.2.4 Regression

A linear regression of the plotted points was used to find the relationship between cooking power and temperature difference in terms of intercept a (W) and slope b (W/C) or P_s=a+b T_d. No fewer than 30 total observations from three different days were employed. The coefficient of determination (R^2) or proportion of variation in cooking power that can be attributed to the relationship found by regression should be higher than 0.75.

2.2.5 Single measure of performance

The value for standardized cooking power, P_s, (W) was computed for a temperature difference, T_d, of 50°C using the regression relationship found.

2.3 Experimental procedure

Experiments were conducted at Centre for Entrepreneurship and Enterprises Development (CEED) University of Maiduguri with the constructed solar cooker without load and with loadon31stMarch 2020 and 1st April 2020. The experiments began at 10:00 am and were continued until 14:00pm. During the experiments, the radiation intensity on a horizontal surface was measured using a digital pyrometer (SPM-1116SD) (accuracy 0.1W/m^2), (MTM-3801) digital thermometer with three (3) channel contact thermocouples (accuracy 0.1^{0}C) was used to measure the temperature at different locations of the cookers; namely; the cooking fluid, the absorber plate and the ambient temperature. In addition, measuring cylinder was used to measure the volume of water. Ambient temperature, absorber plate temperature, initial water temperature, maximum water temperature and boiling water temperature were measured and recorded at 10 minutes intervals. The recorded data was used to determine the performance of the constructed solar cooker, wind speed was measured using a cup vane anenometer (ABH-4224) (accuracy 0.1m/s). The international test standard requirements for temperature range and insolation were applied for the solar box cooker SBC on each day. Figure 3 shows the constructed solar box cooker and measuring equipment.

Figure 3: Constructed solar box cooker and instrumentation

3.0 Results and Discussion

3.1 Stagnation Test

Figure 4 shows the variation in daily solar radiation, absorber plate temperature and the corresponding ambient temperature plotted against time of the day. It is clear that the absorber plate temperature increases towards the noon period, then decreases towards evening and solar radiation increase with increase in hours of the day toward noon with decrease in evening. The figure shows that the maximum absorber plate temperature was achieved by mid-day and was found to be 157.2°C with an instantaneous solar radiation of 821.6 W/m^2 and an ambient temperature of 47.8° C, the result is similar to the findings of Nahar (1994) that achieved 158° C as stagnation in solar box oven with thermal insulation material, compared with 117°C without the thermal insulation material. F_1 was calculated as per Eq. 4 and was found to be 0.132, this value indicates the constructed cooker to be grade A as set by BIS and this value agreed with standard value of $F_1 \geq 0.12$. The high values of F_1 indicate that the cooker has high optical efficiency, high solar radiation and low heat loss factor. The absorber plate reaches (100° C- 150° C) at 2hrs 30min and maintain above 150°C can be attributed to insulation ability of the insulator as indicated by Aremu and Akinoso (2013), in order to reduce the heat loss from the solar box cooker walls it can be insulated with effective insulation materials which have low thermal conductivities of 0.03–0.06 W/m.°C

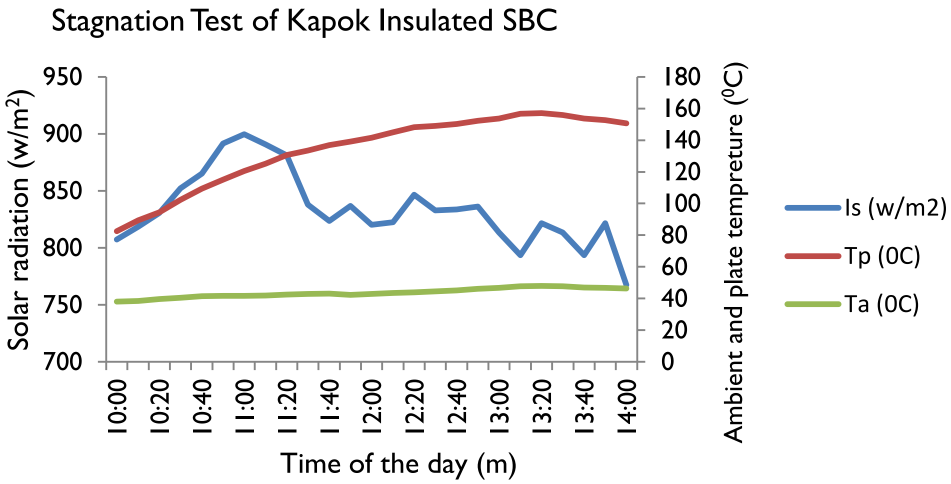

Figure 4: Variation of Absorber Plate Temperature with Corresponding Solar Radiation and Ambient Temperature

3.2 Water Boiling Test

Figure 5 shows the variation in daily solar radiation, water temperature and the corresponding ambient temperature plotted against time in the test day. It clearly indicates increase in water temperature as time of day increases with increasing solar radiation intensity, it was noticed that at the beginning, the water boiling temperature increases due to the heat accumulated inside the solar cooker, the temperature falls down as the solar radiation intensity decreases at solar time of (12:00 noon). It takes 50 minutes for the water temperature to attain 60.2°Cand it takes another 70 minutes before the temperature reaches 92.9°C. Sambo et al. (1993) reported that the required minimum food cooking temperature is 82°C. In the present study the water temperature is higher than the water pasteurization value. Therefore, the results suggest that; the developed solar box cooker can be used for cooking in the study area

(Maiduguri). F_2 was calculated based on Eq. 5 and was found to be 0.598, this value agreed with standard value of $F_2 \geq 0.4$set by BIS. The result is similar to the finding of Harmim et al. (2014) and Mohammed et al. (2013). The higher F_2 value achieved in the present cooker configuration is an indication of better heat retention ability of the cooker insulating material (Kapok). Using equation 3 thermal efficiency (η) was estimated to be 44%.

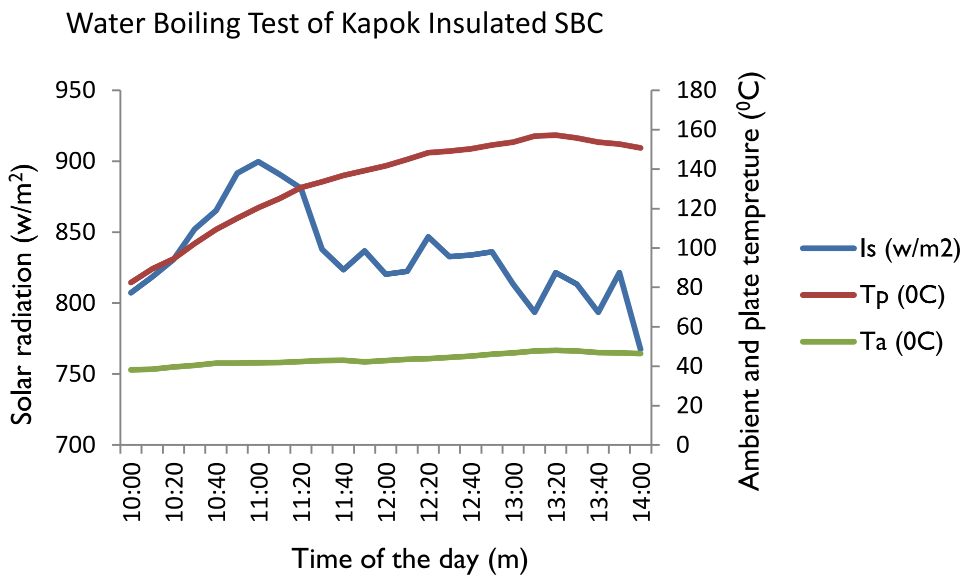

Figure 5: Variation of Water Temperature with Corresponding Solar Radiation and Ambient Temperature

Figure 6 shows the performance of the solar box cooker (Standardized Cooking Power) which has been established versus the temperature differences. It was noticed that the performance for solar box cooker increases as the temperature difference increases. Equations 6, 7 and 8 were used for the computation of interval cooking power (P_i), standard cooking power (P_s) and Temperature difference (T_d) respectively as shown in figure 5.

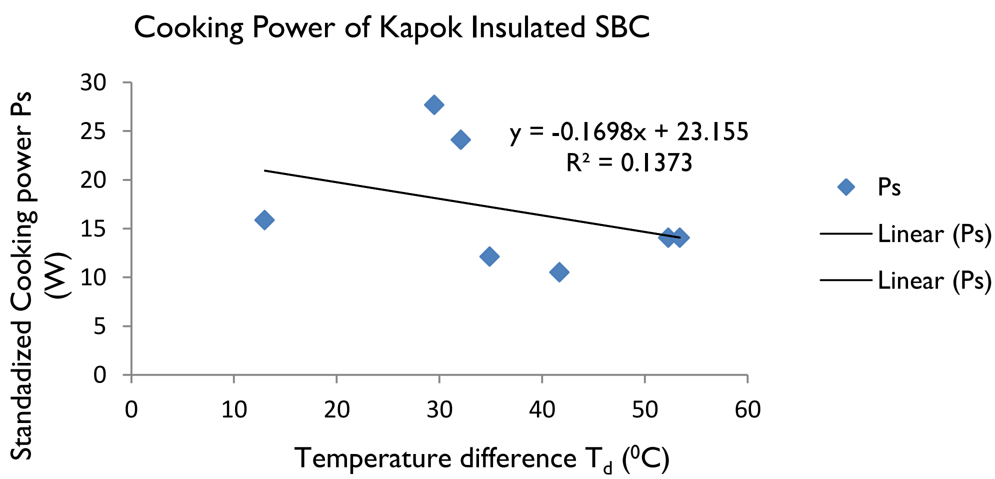

Figure 6: Variation of Standard Cooking Power with Corresponding Temperature Difference

Linear regression was used to find the relationship between energy efficiency and temperature difference in terms of intercept (%) and slope (%/). Figure 5 reveals the cooking power regression equation relation as reported by ASAE (S580.1).

$$P_s = 23.155 - 0.1698T_d \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

The value of the coefficient of determination of the equation (R^2) 0.1373 is less than 0.75 the standard recommended value by ASAE (S580.1). The cooking power at 50^0C temperature difference (P_{50}) was calculated using the generated regression equation and P_{50}= 14.71W. As indicated by figure 5, Standard cooking power directly decreases as the temperature difference increase. The linear regression equation generated is similar to the linear regression equations generated by Folaranmi (2013) and Abdoulkader *et al.* (2017).

4.0 Conclusion

The construction of Solar Box cooker with Kapok fiber as insulator and its performances under Maiduguri climatic weather condition were carried out in this study. The Ambient temperature, absorber plate temperature, solar radiation, water temperature and wind speeds were experimentally measured. The figures of merits F_1, F_2, interval cooking power, standard cooking power were determined and compared with available reviewed literatures. A linear regression equation was also generated and analyzed. The cooker would be helpful to Maiduguri community and other places under similar climatic weather condition.

References

Ademola, KA. And Joseph, CI. 2015. Energetic and exergetic evaluation of box-type solar cookers using different insulation materials. World Academy of Science, Engineering and Technology, International Journal of Biological, Food, Veterinary and Agricultural Engineering, 9(5): 397-403.

Aguyi, G. 2011. Thermal Properties of Selected Materials for Thermal insulations in Uganda. Department of Physics, Makerere University, Makerere.

Akorede, MF., Ibrahim, O., Amuda, SA., Otuoze,AO. and Olufeagba, BJ. 2017. Current Status and Outlook of Renewable Energy Development in Nigeria; Nigerian Journal of Technology (NIJOTECH) 36 (1): 196 – 212.

Aremu, AK. and Akinoso, R. 2013. Potential Use of Box-Type Solar Cooker in Developing Countries, The Journal of the Association of Professional Engineers of Trinidad and Tobago, 41(1): 11-17.

ASABE 2013. ASABE Standards-S580.1, Testing and Reporting Solar Cooker Performance. American Society of Agricultural and Biological Engineers, Nile Road, St. Joseph, Michigan.

Bello, AMA., Makinde, V. and Sulu, HT. 2010. Performance Tests and Thermal Efficiency Evaluation of a Constructed Solar Box Cooker at a Guinea Savannah Station (Ilorin, Nigeria). Journal of American Science, l6(2): 32-38.

Elamin, OMA., Abdalla, IAA. 2015. Design, Construction and Performance Evaluation of Solar Cookers. Journal of Agricultural Science and Engineering, 1(2): 75-82.

Folaranmi, J. 2013. Performance Evaluation of a Double-Glazed Box-Type Solar Oven with Reflector, Journal of Renewable Energy, 2013, Article ID 184352: 1-8.

Funk, PA. 2000. Evaluating the international standard procedures for testing solar cookers and reporting performance. Solar Energy, 68: 1-7.

Garba, MM. and Danmallam, IM. 2014. Techno-Economic and Environmental Impact Analysis of a Passive Solar Cooker for Application in Nigeria. The International Journal of Engineering and Science (IJES), 3(12): 6 –10.

Harmim, A., Merzouk, M., Boukar, M. and Amar, M. 2014. Cooking Development in Algerian Sahara: Towards a Socially Suitable Solar Cooker. Renewable and Sustainable Energy Reviews, 37: 207–214.

Idriss, AI., Omar, AI., Mohamed, MA., Omar, AM. and Dabar, OA. 2017. Thermal Performance Testing and Promotion of Solar Cooker under Djiboutian Climate. International Journal of Engineering and Technology (IJET), 9(3): 2319-8613.

Mohammed, LS., Gwana, AM., Abubakar. M., Mohammed, LM. and Hauwa, LB. 2017. Appraisal of Tree Planting Programmes in Maiduguri Metropolitan, Nigeria. International Journal of Environmental Protection and Policy; 5(6-1): 33-39.

Mohammed, IL., Rumah, UJ. and Abdulrahim, AT. 2013 Performance Testing of a Truncated Pyramid Solar Thermal Cooker. International Journal of Engineering Research and Applications (IJERA), 3(4): 1174-1178.

Mullick, SC., Kandpal, TC. and Sexena, AK. 1987. Thermal test procedure for box type solar cooker. Solar Energy, 39: 353-360.

Nahar, NMM., Mashall, RH. And Brinkworth, BJ. 1994. Studies on a Hot Box Solar Cooker with Transparent Insulation Materials. Energy Conversions and Management, 359: 787–791.

Ozturk, HH. 2004. Energy and exergy efficiencies of a solar box-cooker. International Journal of Exergy, 1(2): 202 -213.

Sambo, AS., Danshehu, BG. and Garba, B. 1993. The Effect of Design Parameters on the Performance of Improved Wood-Burning Stoves. Journal for Solar Energy, 10: 85-94.

Saxena, AV., Pandey, SP. and Srivastav G. 2011. A Thermodynamic Review on Solar Box Type Cookers. Renewable and Sustainable Energy Reviews, 15: 3301–3318.

Ramesh, HC., Modi, VM., Alok, G., Desai, NN., Chaudhary, HS., Bhavsar, S., Kuma, S. and Jain, S. 2018. Performance Evaluation and Cost Economics of Developed Box Type Solar Cooker. International Journal of Current Microbiology and Applied Sciences, 7(12): 1788-1795.

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