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DESIGN, FABRICATION AND CHARACTERIZATION OF AN AUTOMATED INCLINED BOX-TYPE SOLAR COOKER EMPLOYING TRACKING REFLECTORS

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ABSTRACT

An inclined box-type solar cooker employing tracking reflectors with dimensions 700mm x 440mm x 280mm, has been successfully designed and fabricated. The detachable reflectors, which were mounted on the box cooker, were suitably positioned in an east-west configuration on an inclined framework. This automatically tracks the apparent motion of the sun within 15 minutes time interval so as to align with the earth's rotation when displayed under the sun. Thermal performance of the inclined box-type solar cooker has also been compared with that of a conventional box-type solar cooker whose dimensions and make are identical to the inclined box cooker. Testing of the tracking box type solar cooker has been carried out with load and without load conditions at Federal University of Technology Owerri, Imo State, located at Latitude 5^{o}N, Longitude 7^{o}E, Altitude 156m (Altitude 511ft) and 12km south of Owerri capital territory. Experimental results obtained from the field test show that the inclined box-type solar cooker with tracking reflectors attained temperature of 94^{o}C, with efficiency of 93% and boiled water for 1hour 28 minutes. The conventional box-type solar cooker attained a temperature of 91^{o}C, with efficiency of 90.9% and boiled water for 1hour 36 minutes. The tracking box cooker was found to be more efficient and effective than the conventional box cooker. Meteorological variables like Air Temperature, Irradiance, Relative Humidity and Wind speed were also obtained to investigate their effects on the performance of the box cookers.

KEYWORDS: Tracking reflectors, box-type solar cooker, temperature, efficiency, effectiveness and cooking power.

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1. INTRODUCTION

The sun, which is the primary source of energy for our planet Earth, has played a major role in the activities of man and his environment in drying of materials, foodstuffs, wood seasoning, heating and house warming etc. Most recent scientific technologies have channeled the usefulness of Solar Energy in the area of cooking, drying and heating. In recent times, Solar Energy conversion for cooking purposes has led to the construction of solar box cookers, using reflectors to trap the radiant energy.

The utilization of solar cooking systems dates back (18^{th} century). The first known solar cooker was pioneered by a Swiss naturalist Horase Nicholas de Saussure (1740 – 1799). He built a black, insulated box cooker with several glass covers and realized maximum temperature of 88^oC (191^oF). This solar box cooker was without reflectors (Meinel, A.B., and Meinel, M.P. 1976, Cheremisinoff and Regino 1978). In Turkey, Numan*et al* (2012), built a two reflector box type cooker and realized a maximum temperature of 80.5^oC. In Nigeria, Uhuegbu, (2011), built a wooden solar box cooker without reflectors and realized maximum temperature of 72^oC. It was observed that the box cooker has no reflectors to maximally trap radiant energy falling on the box cooker aperture. This would have boosted the input power, so the temperature realized by the cooker was not high enough for coking.

Records have shown that 15% of total world's population and 50% of Nigerians rely on burning wood or dried dung for cooking their food without considering the environmental impact of deforestation (WHO, 1992). 1.6 million (about 1%) of Nigeria's population die annually as a result of air pollution (smoke) in the houses (WHO, 1984, 1992, 2004). 1.5 to 2 million deaths were attributed to exposure to Indoor Air Pollution in developing countries in 2000 (WHO, 2006).

The effect of smoke on man is enormous; its health implications include poisonous gases like Aldehydes, Benzene and Carbon monoxide. Diseases like Acute Lower Respiratory Infections (A.L.R.I), Chronic Obstructive Pulmonary Disease (C.O.P.D), Cataracts and blindness, lung cancer, tuberculosis, premature births and low birth weight are also suspected of being caused by Indoor Air Pollution (Pokhrel*et al*., 2005). 1kg of burning wood produces tiny particles of soot which can clog and irritate the bronchial pathways, and the Nigerian woman often cook with infants on their backs, exposing both mother and child to toxic fumes (Pokhrel et al., 2005). 50% of pneumonia deaths among children under 5 years of age are due to particulate matter inhaled from Indoor Air Pollution (Mukesh*et al*., 2008).

Solar cooking has become a promising viable option in tropical rural areas since it helps in curtailing deforestation and desertification. Its eco-friendly advantages ranges from non- contribution of unwanted heat inside the house, no smoke is produced as a product of combustion, it does not produce ashes and soot, which make the home dirtier unlike the fire-based cooking, children cannot be burned by touching many types of solar cookers, which is usually encountered when the children are cooking with the open fire, solar cookers are not fire hazards. The indoor concentration of health-damaging pollutants from a typical wood-fire cooking stove creates carbon monoxide and other noxious fumes at anywhere between seven and 500 times over the allowed limits, but this is contrary to the workability of a solar cooker. Cooking with solar cookers preserves greater percentage of nutrient content in the food being cooked (Alozie*et al*., 2010).

In an attempt to harness the abundant energy source, reflector systems have been introduced into the construction of the solar box cooker. The box type solar cooker, however, is still the preferred option for most users because of its small size and simple handling and operational requirements.

The present work aims at developing a trackable solar cooker which can enhance heat capacity of a box type solar cooker by harvesting of solar energy into the box for efficient cooking, using tracking reflectors. To achieve maximum effect of the reflectors, its daily tracking was ensured every 15 minutes and positioned horizontally in accordance to the latitude of site location, to implement the altitude and azimuth angles along with the hour angle and declination angles with respect to the celestial equator.

The objectives of this work include;

i. To utilize a solar sensor device to track the solar irradiation and relay it to the mechanical motor whose planetary gears will move with the angular radius of the sun and with the electronic programmed time device, so that the reflectors are adjusted to the angle where solar intensity is captured at its peak.

ii**.** To measure and compare the temperatures of the tracking solar box cooker and the conventional solar box cooker.

iii**.** To calculate and compare the efficiencies of the tracking solar box cooker and the conventional solar box cooker.

2. METHODOLOGY

2.1 DESIGN AND CONSTRUCTION

The materials for the design were locally sourced. Plywood was used for inner box construction because it does not allow heat passage, and it enhances neatness. The dimensions of the inner box are 590mm x 350mm x 260mm, with wall thickness of 0.5mm, painted black. The inner box was laminated with Aluminium foil to act as reflector, for bouncing back the heat to the cooking pot. Aluminium sheet was used on the width of the cooker to act as collector of heat and this reflect heat back to the hot plate and cooking pot. The outer box was constructed with hardwood of thickness 1mm, the dimension of the outer box are 700mm x 440mm x 280mm, and also painted black. The thickness of the glass cover used for this work is 4mm, with aperture area of $195000mm^2$. The glazing is designed as a double sliding glass for the two cooking chambers with perfect insulation at the middle, free from bubbles and rough surface (see figure 1a). The dimension of the absorber plate was 310mm x 295mm, with sheet thickness 0.5mm and painted black. The cooking pot was made of Aluminium with thickness 0.5mm, diameter 150mm and depth 90mm. Space between the side and bottom of both the boxes were 25mm each, and were lagged with fiberglass and compressed asbestos foil fiber 2mm thick. When radiation from the sun is incident on the mirror, it is reflected on the opposite direction in such a way that it is absorbed by the glass cover of the box which serves as the lid. The dimension of the mirror used for the reflectors was 650mm x 300mm; the mirrors were sub-sized into 50mm x 50mm, to enhance the input power into the cooking chamber of the box (see figure 1c). The reflectors were inclined at 45^0. The cooker was placed on an inclined movable frame facing the sun, keeping the longer side at vertically inclined position. The inclination of the box cooker can easily be changed from 15^o to 45^o with respect to the ground by the automatic inclined tracking stand attached at one side of the box (see figure 1c).

Figure 1(a):Tracking Box CookerFigure 1(b):Conventional Box Cooker

Figure 1(c):Both box cookers showing sub-sized mirror reflectors to boost input power, and the double sliding glass cover for the cooking chambers with perfect insulation.

2.2 DESIGN THEORY

The inclined box type solar cooker employing tracking reflectors optimized the astronomical tracking method, which employs the longitude and latitude data of the field test location. It has the advantage of simple programming, high degree accuracy and less error. The starting position of the tracker was always same from day to day; the tracker was programmed to return to its initial position after the day's test.

2.3 ALGORITHM FOR SOLAR TRACKER

The solar altitude (θ_e) and azimuth (θ_a) were computed in accordance with the location. The tracker device was positioned horizontally to implement the altitude and azimuth angles along with the hour angle and declination angle. The solar altitude and azimuth are given by the equations below

$$\sin\theta_e = \sin\delta\sin\Phi + \cos\delta\cos\Phi\cos H \qquad (1)$$

$$\sin\theta_a = -\frac{\cos\delta\sin H}{\cos\theta_e}$$

Where θ_e = Solar altitude

θ_a = Solar azimuth

δ = Declination

Φ = Latitude of observer

H = Hour angle (Seung, *et al*., 2009).

2.4 SUNRISE AND SUNSET TIME

The solar tracking system was returned to its initial position after sunset, so as to ensure that it does not start tracking the sun after the sun appears above the horizon. The sunrise and sunset time were calculated using the following equations

$$T = H + \alpha - (0.06571 \times t) - 6.622 \qquad (3)$$

For sunrise, we have t = N + [(6 – lngHour)/24]

For sunset, we have t = N + [(18 – lngHour)/24]

T = Sunrise or Sunset time

H = Hour angle

N = Day of year

α = Right ascension

lngHour = (longitude)/15 (Seung, *et al*., 2009).

2.5 EFFICIENCY (Ƞ): The efficiency is not a function of collector's temperature, rather is a function of the difference between the collector temperature (T_c) and the ambient temperature (T_a), that is, $(T_c - T_a)^oC$.

The efficiency increases with decrease in temperature difference between collector temperature and ambient temperature. Efficiency decreased with decreasing solar radiation.

The efficiency is computed using the relationship given by (Felix, *et al*., 2002).

EFFICIENCY

$$\boldsymbol{\eta} = \boldsymbol{n_0} - \boldsymbol{a_1}\left(\frac{T_c - T_a}{E_a}\right) - a_2\frac{(T_c - T_a)^2}{E_a} \qquad (4)$$

n_o = Optical heat transfer coefficient.

$n_o = \alpha\tau F$

α = Absorption factor of absorber plate = 0.93

τ = Transmission factor of cover = 0.895

F = Absorber efficiency factor = 0.945

a_1 = Linear heat transfer coefficient = $2.6 W/m^2K$

a_2 = Quadratic heat transfer coefficient = $0.01 W/m^2K^2$

E_e = Solar Irradiance = $1000 W/m^2$

2.6 POWER (E): Energy or power radiated by absorber plate is dependent on the collector temperature $(T_c)^oC$. Energy increased as collector temperature increased. Energy (E) per second radiated by the absorber plate is computed by the Stefan Boltzmann formula of blackbody radiation for total power.

$$E = eA\delta T_c^4 \qquad (5)$$

A = surface area of the absorber plate.

e = emissivity. T_c= collector temperature.

σ = Stefan Boltzmann's Constant = 5.67 x 10-8W/m^2K^{-4}.

2.7 COOKING POWER OF THE COOKER (P): This is defined as the rate of useful energy available during heating period. The cooking power is computed using the relationship given by (Funk, 2000).

$$P = \left(\frac{T_{w2} - T_{w1}}{t}\right)M_w C_{pw} \qquad (6)$$

P = cooking power. T_{w2} = final water temperature

M_w = mass of water T_{w1} = initial water temperature.

C_{pw} = specific heat capacity of water. t = time

2.8 EFFECTIVENESS (ε) OF THE COOKER: Effectiveness in terms of efficiency in percentage is illustrated as to effectiveness of solar cooker in converting the Insolation falling on it to heat energy.

It is calculated using the relationship given by (Funk, 2000).

$$\varepsilon = \left(\frac{I_{ay} - I_y}{I_0}\right) x100\% \qquad (7)$$

Iav = average Insolation = 1000W/m Io = average theoretical Insolation = 700W/m^2

Iγ = energy ε = Effectiveness of the cooker.

3. RESULTS

Both solar box cookers were displayed under the sun from September, 2012 to December, 2012; to checkmate its workability as well as check for variation of temperature between both cookers from late hours in the morning to late afternoon with the aid of inserted thermometer (0^{o}C to 150^{o}C). The data for the meteorological variables (Air temperature, Relative Humidity and Wind Speed) were obtained with the aid of multidigital environmental meter DLAF8000, while the Irradiance data was obtained using kipp-zonen CM 21 handheld pyranometer. The temperatures of the box cookers were obtained hourly, while the meteorological data were obtained every 15 minutes from 8.00am to 6.00pm respectively. The maximum value data obtained for time, maximum solar cooker temperature, air temperature, irradiance, relative humidity and wind speed for the months of September, October, November and December 2012 are presented in Tables 1 to 4.

TABLE 1: MAXIMUM DATA OBTAINED FOR SEPTEMBER, 2012.

S/N	TIME (HRS)	TRACKING SOLAR BOX COOKER TEMP(^{O}C)	CONVENTIONAL SOLAR BOX COOKER TEMP(^{O}C)	AIR TEMP(^{O}C)	IRRADIANCE (W/m^2)	RELATIVE HUMIDITY (%)	WIND SPEED (m/s)
1	8.00	34.0	32.0	27.0	77.0	82.0	0.5
2	9.00	37.0	35.0	28.4	164.0	76.0	0.5
3	10.00	42.0	39.0	28.7	337.0	74.8	1.0
4	11.00	49.0	45.0	30.1	413.0	73.3	0.7
5	12.00	56.0	51.0	31.1	476.0	67.8	1.0
6	13.00	63.0	58.0	32.5	584.0	66.3	0.8
7	14.00	67.0	62.0	33.1	641.0	62.2	0.6
8	15.00	68.0	62.0	33.6	661.0	61.7	0.7
9	16.00	66.0	59.0	31.4	447.0	66.7	1.0
10	17.00	61.0	53.0	29.9	247.0	70.9	0.8
11	18.00	55.0	44.0	28.3	135.0	73.2	0.4

TABLE 2: MAXIMUM DATA OBTAINED FOR OCTOBER, 2012.

S/N	TIME (HRS)	TRACKING SOLAR BOX COOKER TEMP(^OC)	CONVENTIONAL SOLAR BOX COOKER TEMP(^OC)	AIR TEMP(^OC)	IRRADIANCE (W/m^2)	RELATIVE HUMIDITY (%)	WIND SPEED (m/s)
1	8.00	41.0	38.0	29.7	402.0	73.2	0.5
2	9.00	50.0	47.0	31.9	487.0	71.0	0.4
3	10.00	58.0	54.0	32.6	560.0	69.1	0.7
4	11.00	63.0	59.0	34.1	681.0	62.6	1.0
5	12.00	68.0	64.0	36.0	723.0	58.2	0.7
6	13.00	80.0	75.0	36.7	822.0	56.4	0.5
7	14.00	87.0	82.0	37.5	890.0	51.3	0.8
8	15.00	83.0	76.0	37.0	794.0	55.7	1.0
9	16.00	76.0	68.0	34.8	722.0	57.6	0.5
10	17.00	70.0	61.0	32.4	480.0	60.3	0.6
11	18.00	64.0	53.0	30.6	274.0	66.8	1.1

TABLE 3: MAXIMUM DATA OBTAINED FOR NOVEMBER, 2012.

S/N	TIME (HRS)	TRACKING SOLAR BOX COOKER TEMP(^OC)	CONVENTIONAL SOLAR BOX COOKER TEMP(^OC)	AIR TEMP(^OC)	IRRADIANCE (W/m^2)	RELATIVE HUMIDITY (%)	WIND SPEED (m/s)
1	8.00	48.0	44.0	28.7	284.0	79.0	0.4
2	9.00	54.0	49.0	30.4	459.0	77.0	0.6
3	10.00	63.0	58.0	32.3	664.0	71.4	0.7
4	11.00	71.0	65.0	33.1	723.0	64.9	1.2
5	12.00	79.0	73.0	34.9	794.0	60.2	0.8
6	13.00	90.0	85.0	36.4	911.0	57.0	0.4
7	14.00	86.0	81.0	35.9	870.0	58.1	0.8
8	15.00	84.0	78.0	33.4	841.0	60.9	0.8
9	16.00	78.0	69.0	31.8	437.0	65.4	1.1
10	17.00	74.0	63.0	29.9	288.0	70.6	1.0
11	18.00	68.0	57.0	27.9	125.0	75.1	1.0

TABLE 4: MAXIMUM DATA OBTAINED FOR DECEMBER, 2012.

S/N	TIME (HRS)	TRACKING SOLAR BOX COOKER TEMP(°C)	CONVENTIONAL SOLAR BOX COOKER TEMP(°C)	AIR TEMP(°C)	IRRADIANCE (W/m²)	RELATIVE HUMIDITY (%)	WIND SPEED (m/s)
1	8.00	44.0	40.0	27.9	180.0	84.0	0.8
2	9.00	50.0	46.0	31.9	362.0	70.7	0.5
3	10.00	61.0	57.0	32.8	650.0	65.6	1.2
4	11.00	73.0	70.0	33.6	765.0	61.4	0.9
5	12.00	83.0	80.0	35.2	847.0	55.0	1.4
6	13.00	94.0	91.0	38.8	981.0	51.0	0.7
7	14.00	91.0	86.0	37.4	935.0	54.8	1.6
8	15.00	90.0	84.0	33.5	906.0	57.3	0.8
9	16.00	83.0	74.0	33.0	635.0	60.1	0.6
10	17.00	78.0	67.0	32.2	415.0	63.3	1.5
11	18.00	70.0	55.5	30.5	198.0	69.8	0.9

TABLE 5: MINIMUM MONTHLY AVERAGE OF METEOROLOGICAL VARIABLES FOR 2012.

MONTH	AIR TEMP(°C)	IRRADIANCE (W/m²)	RELATIVE HUMIDITY (%)	WINDSPEED (m/s)
SEPTEMBER	26.3	107.0	57.0	0.1
OCTOBER	27.4	141.0	55.0	0.1
NOVEMBER	27.5	155.0	54.4	0.1
DECEMBER	28.4	195.0	52.5	0.2

TABLE 6: MAXIMUM MONTHLY AVERAGE OF METEOROLOGICAL VARIABLES FOR 2012.

MONTH	AIR TEMP(°C)	IRRADIANCE (W/m²)	RELATIVE HUMIDITY (%)	WINDSPEED (m/s)
SEPTEMBER	36.0	859.0	83.0	1.8
OCTOBER	36.3	910.0	80.5	2.0
NOVEMBER	37.0	1073.0	80.0	2.3
DECEMBER	38.0	1095.0	78.5	2.5

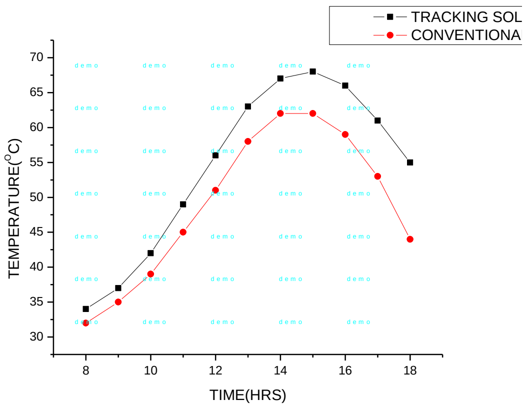


Figure 2: Graph of Temperature against Time for September, 2012.

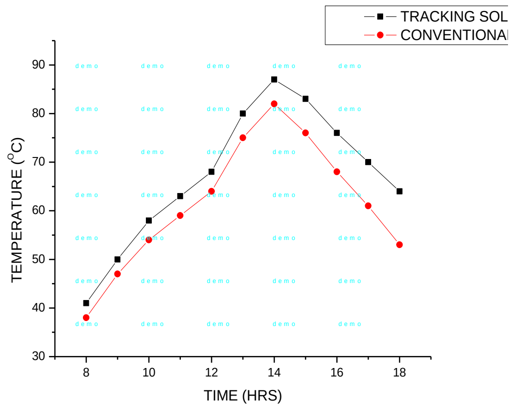


Figure 3: Graph of Temperature against Time for October, 2012.

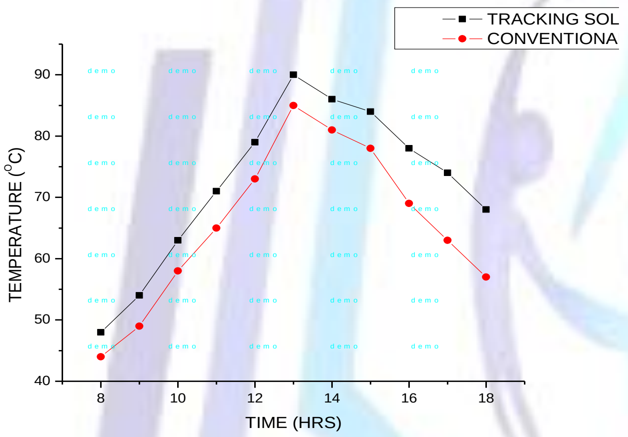


Figure 4: Graph of Temperature against Time for November, 2012.

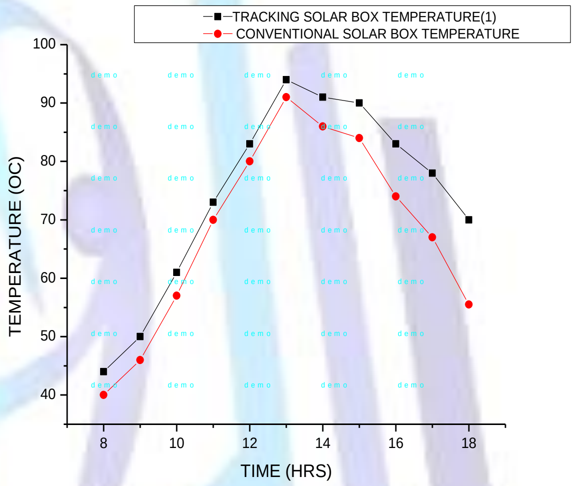


Figure 5: Graph of Temperature against Time for December, 2012.

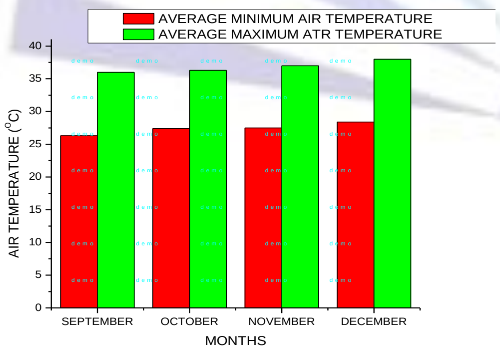


Figure 6: Graph of Air Temperature against Months from September to December, 2012.

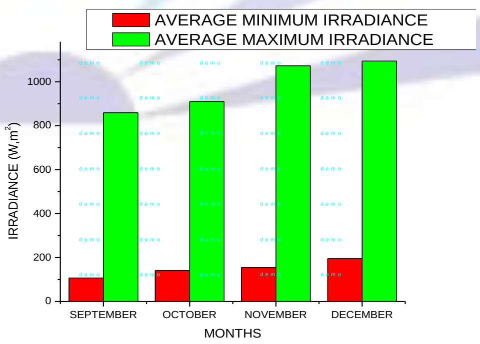
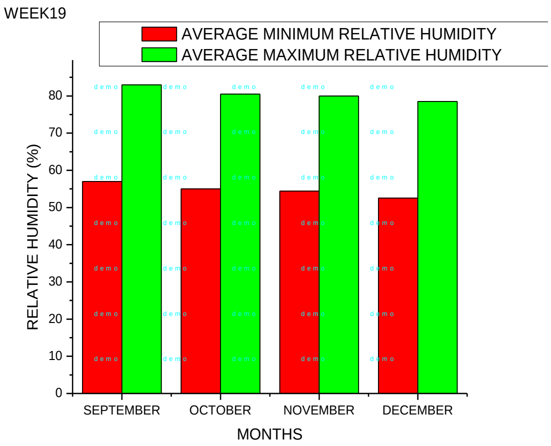


Figure 7: Graph of Irradiance against Months from September to December, 2012.



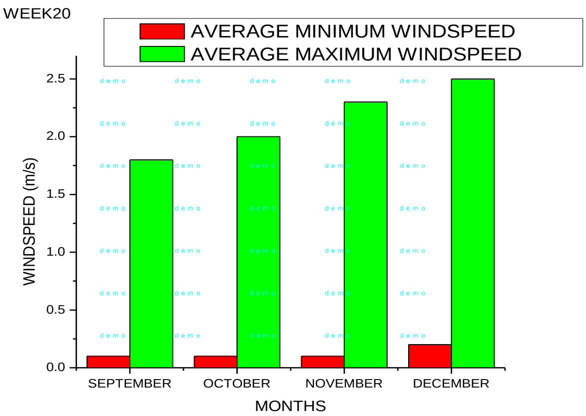


Figure 8: Graph of Relative Humidity against Months from September to December, 2012.

Figure 9: Graph of Wind speed against Months from September to December, 2012.

In addition, using the test method by Funk to calculate the test parameters, the results were summarized in the table 7 below.

TABLE 7: SUMMARY OF RESULTS

PARAMETERS CALCULATED	TRACIKING BOX COOKER	CONVENTIONAL BOX COOKER
EFFICIENCY (%)	93.0	90.9
COOKING POWER (W)	64.0	59.0
NORMALIZED POWER (W)	44.8	41.3
ENERGY (J)	64.2	62.7
EFFECTIVENESS (%)	97.9	97.9
STANDARD COOKING TIME (S)	5280	5760
TOTAL AMOUNT OF HEAT (kJ)	195	195
MAXIMUM TEMPERATURE REACHED (^{o}C)	94.0	91.0

4. DISCUSSION

From the data plotted for the month of September, it showed that both solar box cookers had low temperatures in the morning hours from 8.00am to 11.00am, relatively high temperatures are observed between 12noon and 4.00pm before the heat started to decrease due to sunset.

The maximum temperatures recorded for the month of September were 68^{o}C and 62^{o}C for both tracking and conventional box cookers respectively (see Table 1), these temperatures cannot be used in boiling water or cooking food. September data showed that both solar box cookers cannot perform well during rainy season; this means that the solar cooker may not be possibly used for cooking during this period.

For the month of October, an increase in both box cooker temperatures were observed as the rainy season was gradually ceasing, maximum temperatures recorded were 87^{o}C and 82^{o}C for both tracking and conventional solar box cookers respectively (see Table 2).

For the month of November, a better improved solar box cooker temperature were observed, depicting the arrival of dry season, maximum temperatures recorded were 90^{o}C and 85^{o}C for both tracking and conventional solar box cookers respectively (see Table 3).

The month of December recorded the highest temperatures for both cookers; 94^{o}C was recorded for the tracking solar box cooker while 91^{o}C was recorded for the conventional solar box cooker (see Table 4).

From the data plotted for the four months, increasing trends of temperature were observed as the rainy season gave way for the dry season. It was also observed that the highest temperatures were obtained from 12noon and 4.00pm (see Figures 2-5), before the heat starts to decrease due to sunset. This shows that the best time to cook with the solar box cooker is between the hours of 11.00am and 4.00pm on sunny days because an enhancement of temperature was observed at 11.00am.

The results also draws an inference that the best season to make good use of the solar box cooker is during dry season, so as to maximize efficiency and effectiveness, since the temperatures observed during the rainy season was not good enough to boil water or cook food.

From the data plotted, it was also observed that the temperatures recorded for the tracking solar box cooker hourly was higher than the temperatures recorded for the conventional solar box cooker. This implies that the tracking reflectors were able to harness more of the radiant intensity falling on the earth and on the aperture of the tracking box cooker with minimal loss; while the conventional solar box cooker suffered some loss of temperature as it was kept stationary without tracking the apparent motion of the sun.

From the data obtained, the tracking solar box cooker has better efficiency than the conventional solar box cooker.

The meteorological variables were also observed and recorded so as to check the variations in season between the four months during which the field work were carried out (see Tables 5 and 6).

From the meteorological data plotted, it was observed that the air temperature is directly proportional to the irradiance measured, that is, the air temperature increases as the irradiance increases. Both variables of air temperature and irradiance were inversely proportional to the relative humidity, that is, the higher the irradiance and the air temperature, the lower the relative humidity. The data of the wind speed recorded had no mathematical connection with the other three meteorological variables.

Monthly computation of the meteorological variables evidently depicted the advancement in trends in terms of the solar box cooker temperatures, air temperatures and irradiance as the rainy season gave way for the dry season. The amount of solar radiation energy available per day was computed as monthly average and showed increase from September to December (see Figures 6-9). It was also observed that the solar radiation energy was at its peak within the cooking time interval from 12noon to 4.00pm. The data also showed that during rainy season, there was much availability of cloud cover, which negatively affected the availability of energy, thereby reducing the cooking temperature as seen in the data in the month of September (see Table 1).

5. CONCLUSION

We have designed, fabricated and tested an automated inclined box type solar cooker capable of cooking food in tropical areas where the sun's radiation is in abundance.

From all parametric conditions associated with thermal performance test calculations, between the inclined box type solar cooker with tracking reflectors and the conventional box type solar cooker, it is clearly evident that the inclined box type solar cooker is more effective and efficient than the conventional box type solar cooker (see Table 7).

Also observed were the direct impact of meteorological variables on the efficiency and effectiveness of both box cookers. We observed that an increase in Irradiance led to a proportionate increase in Air temperature and decrease in Relative Humidity. Wind velocity was curtailed to its minimum (see Tables 5 and 6), as the test site was void of windy area to avoid heat loss by convection, thereby reducing cooking time.

Tables 1-4, shows that the best cooking time is from 11.00am – 4.00pm, and is not possible to solar cook on cloudy or rainy days as seen in Table 1 of September, 2012, which depicts a rainy season month.

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