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Comparative Analysis of a Foiled Interior and Black Interior Box-Type Solar Cookers

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Abstract - *Two box type solar cookers with different interior (foil and black-painted interior) were developed and compared using stagnation, water boiling and controlled cooking tests. Black painted interior solar cooker attained stagnation temperatures of 117, 122, 127 and 131 °C while foiled interior cooker attained stagnation temperatures of 108, 120, 124 and 121 °C respectively at an average solar intensity of 716.74, 895.89, 946.12 and 1075.1 W/m2 for the four days of the experiment. Foiled interior solar cooker boiled one liter of water for 145, 50 and 105mins while black painted interior solar cooker boiled the same volume of water for 95, 40 and 70mins. Figures of merit values were calculated from stagnation and water boiling test, foiled interior cooker shows F_1 and F_2 values of 0.11-0.14 and 0.21-0.25 while black interior cooker showed 0.12-0.16 and 0.22 – 0.26 respectively. The controlled cooking test performed by cooking different kinds of food (egg, rice, yam and beans) showed that foiled interior solar cooker boiled a piece of egg after 75mins, cooked 400g of rice after 90mins, 700g of yam after 85mins and 500g of beans after 190mins while black painted interior cooker boiled a piece of egg after 55mins and cooked the same mass of rice, yam and beans after 80, 70 and 180mins respectively. Figures of merit values obtained for the two cookers were comparable with commercial box type solar cookers and regardless of the prevailing weather conditions the black painted box type interior solar cooker performed better than foiled interior box type solar cooker.*

Keywords - solar cooker, water boiling test, stagnation test, controlled cooking test, figures of merit

1. INTRODUCTION

Food is essential for the survival and existence of man but most foods consumed by human beings are cooked as cooking enhances the nourishment of food. Mohood and Powar (2011) reported that cooking is the most important energy consuming operation in the domestic sector and it requires the use of fuel wood (charcoal, firewood and sawdust) in rural areas and other sources of energy (like electricity, gas and kerosene) in developing countries. The supply of electricity have been irregular in some developing countries, the use of cooking gas and kerosene have incurred a higher cost on end-users while the collection and gathering of firewood have been reported to have grave consequences on forest conservation and sustainable forest resource management. Emerhi (2011), reported that in Nigeria, the demand for fuel wood is expected to have risen to about 213.4 x 10^3 metric tonnes, while the supply would have decreased to about 28.4 x 10^3 metric tonnes by the year 2030 in Nigeria.

A transition to sustainable energy system is therefore urgently needed in the developing countries such as Nigeria (Stout and Best, 2001) which should be relatively cheap, abundant in supply and friendly to the atmosphere. Solar energy from the sun generated from nuclear fusion can be used for cooking foods and also as a mitigation tool with regards to global climate change, deforestation and economic debasement of the world's poorest people (Rikoto and Garba, 2013). Adebiyi (1984) reported that solar energy can be used for cooking most foods which requires moderately high temperature usually well in excess of 100 °C.

1.1 Solar cookers

There are various types of solar cookers including the concentrating solar type, parabolic solar type, panel solar type, double exposure solar cookers, thermal storage type solar cookers, hot box solar type, square and rectangular box type solar cookers. However, the box type solar cooker was found to accommodate all kinds of food under prevailing environmental conditions. The box-type solar cooker may be the solar oven type, direct focusing and indirect focusing types depending on size, materials used, insulation and material of construction. Generally, the box type solar cooker is made up of two (2) boxes with insulations between them, an absorbing plate (placed on the bottom of the inner box), a glass cover and a reflective lid. The objective of this research work was to construct a foiled interior and black-painted interior box-type solar cookers and comparatively evaluate the two types of box-type solar cookers.

2. MATERIALS AND METHODS

The materials used for the comparative evaluation of the solar cookers include: cooking pots (made of aluminum to improve heat transfer), solar meter (to measure the intensity of solar radiation), digital multi-meter (to measure the inner cooker temperature, water

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temperature and cooling temperature), stopwatch (to measure time interval between two successive readings), measuring beaker (to measure the volume of water used to cook food items), weighing balance (to measure the mass of food items during cooking test) and other materials like dusters to clean the reflective surfaces of the cooker and measuring tape.

2.1 Construction of the Box- Type Solar Cookers

The two box type solar cookers with different interiors were developed using plywood (thickness 10 x 12.5 mm) for the outer box. The plywood was used for making the base (760 x 760 mm) and the sides (760 x 200 mm), the cut sides of the box were coupled to the base of the box with a 1.5 inches nail, minimal numbers of nails were used to limit the amount of heat loss by conduction, four slanting plywood were also cut and placed at an inclined angle of 35 $^{\circ}$C to the horizontal with a length of 600 mm, opposite sides 360 mm, height 120 mm and a slant height 170 mm thus forming a trapezoidal shape. Four elevating battens of 25mm x 25mm x 80 mm height made from hardwood were used to raise the level of the inner compartment, sawdust mixed with glue was used to seal the joints to prevent heat losses Glass frame was constructed and placed on the wood with a clearance of 0.5 mm between to accommodate dimensional changes and prevent breakage, the glass frame was coupled to the outer compartment using hinges and nails to enable opening and a reflector of aluminum foil was applied on the surface of the first box and the second box had a 1.00 mm thick aluminum sheet painted dull black and four rotating tyres were incorporated to the base of the cookers to aid easy maneuvering and movement of cookers without being raised or lifted. The solar cookers are shown in Plate 1

Plate 1: The Foiled Interior and Black Painted Interior Box Type Solar Cookers

2.2 Performance Index

Various researchers have worked on the development and testing of solar ovens (Kamen and Lankford, 1990; Metcalf and Logvin, 1981; Fabersunne et al., 1986, Mulick et al., 1996; Nandwani, 1992; Saxena et al., 1987; Ramaswany et al., 1997; Funk and Larson, 1994; Adegoke and Akintunde, 1999; El-Sebail et al., 1994; El-Sebail, 1997; El-Sebail and Aboul-fnein, 1997; Curin et al., 1994) and they all recommended the use of energy from the sun for various operations. Rikoto and Garba (2013) reported the comparative analysis of finned and unfinned solar cooking where 300 g of rice was cooked for 120 and 150 mins for the finned and unfinned solar cooking respectively. Mohod and Powar (2011) performed a cooking performance test of multi-reflector foldable type solar cooker and reported 70 mins for cooking 100 g of rice with 200 g of water, 80 mins for cooking 200 g of potatoes with 400g of water.

A standardized measure that is independent of oven parameters and solar intensity information is needed for direct comparison of oven performance. Mullick et al., (1996) provided series of test procedures for rating performance of box type solar cookers, the insolation (W/m^2) on a horizontal oven surface, H, is used to normalize the index as given in the Equation 1;

$$I=(T_{oven}- T_{amb})/ H \qquad (1)$$

Where:

T_{oven} is the oven temperature (°C)

T_{amb} is the ambient temperature (°C)

Furthermore, ambient and peak temperature data for the ovens during the prolonged field use is of great value in analysis of oven effectiveness and very simple equipment is sufficient for this data to be recorded by the people using these oven on a day-to-day basis, the parameter free index is obtained from the relation:

$$PI = \frac{\int (T_{oven} - T_{amb})\, dt}{\int (T_{amb})\, dt} \qquad (2)$$

Where:

PI is the performance index of the solar cookers and other parameters remain as earlier defined.

2.3 Thermal Performance Testing Parameters

Three different tests were carried out to determine the thermal performance and efficiency of the cookers. These tests include: stagnation test, water boiling test and controlled cooking test.

i. Stagnation Test:

This was used to determine the thermal performance of the solar cookers. The cookers were operated individually without cooking (under no load) to determine the maximum possible temperature attainable at a particular point in time. The cookers were placed in an open environment with the window glass and reflection lid thoroughly cleaned; thermocouples were used to obtain the average temperature of the absorber plate, internal air and ambient temperature. The boxes were aligned to face the east at noon and west at the afternoon, thermocouple readings were recorded at intervals. The test was repeated and carried out on four different days.

ii. Water Boiling Test:

Carried out to determine the time it takes the cookers to boil a known volume of water. Thermocouple wire was fixed to run through a small hole made on the pot lid placed within the pot and not touching the base. The readings were taken at five (5) minutes intervals and concluded when the water reaches boiling point, water temperature, inner air temperature, ambient temperature and boiling time were all measured using stop watch and thermocouple for three different days. Various researchers have previously used the water boiling test including Yahaya and Ibrahim (2012); Onuegbu et al. (2011).

iii. Controlled Cooking Test:

The weight of the food to be cooked was obtained, lowest volume of water needed to cook the particular food was introduced and the total mass of pot and mixture was obtained also, the cooker was preheated and the pot was placed therein, cooking time was noted and recorded. The procedure was repeated for various kinds of staple foods including rice, beans, eggs and yam.

2.3.1 Determination of Figures of Merit

The procedures for testing the solar cookers depend on climatic parameters. The evaluation of the cookers was extended to parameters that are independent of climatic factors from which two figures of merit denoted by F_1 and F_2 can be determined (Saxena et al., 1987). The first figure of merit (F_1) was obtained by monitoring the time/temperature profile of an unloaded box solar cooker set under the sun. The highest temperature attainable inside the cooker with the corresponding ambient temperature and the corresponding insolation were noted and the first figure of merit was obtained from equation 3:

$$F_1 = \frac{(T_{ps} - T_{as})}{G_s} \qquad (3)$$

Where:
F_1 is the first figure of merit
T_{ps} is the stagnation temperature (°C)
T_{as} is the ambient temperature (°C)
G_s is the solar insolation at stagnation (W/m2)

The second figure of merit was obtained from the water boiling test and calculated from equation 4:

$$F_2 = \frac{F_1(M_c)\,w}{A(t_2 - t_1)} \log e \left[\frac{1 - \frac{TW_1 - T_a}{F_1 G}}{1 - \frac{TW_2 - T_a}{F_1 G}}\right] \qquad (4)$$

Where:
F_2 is the second figure of merit
M is the mass of water (kg)
C is the specific capacity of water (J/kg°C)
$t_2 - t_1$ is the time taken for water to boil from T_{w1} to T_{w2} (secs)
Ta is the average ambient temperature over time period $t_2 - t_1$ (°C)
G is the average solar radiation over a time period $t_2 - t_1$ (W/m^2)
T_{w1} is the temperature of water at time t_1 (°C)
T_{w2} is the temperature of water at time t_2 (°C).

3. RESULTS AND DISCUSSION

The comparative evaluation of a foiled interior box type and black painted interior solar cookers was carried out using stagnation test, water boiling test and controlled cooking tests. Obtained results are reported and discussed below:

i. Stagnation Test:

The test was carried out for four (4) different days at an average insolation of 716.74, 895.89, 946.12 and 1075.1 W/m2 respectively; the temperature of the absorber plate (Tap), inner air temperature of the cookers (Tia) and ambient temperatures (Tamb) were noted and recorded. The first and second figure of merit (F1 and F2) were calculated from the stagnation and water boiling test for each cooker and the results obtained are presented in Table 1.

Table 1: Stagnation Temperatures of Foiled Interior and Black-painted Interior Solar Cooker

	Foiled interior solar cooker					Black painted interior cooker				
Parameter	T_{ap} (°C)	F_1	F_2	T_{ia} (°C)	T_{amb} (°C)	T_{ap} (°C)	T_{ia} (°C)	F_1	F_2	T_{amb} (°C)
Day 1	108	0.11	023	86	34	117	73	0.12	0.23	34
Day 2	120	0.12	0.25	92	36	122	79	0.14	0.26	36
Day 3	124	0.14	0.25	50	37	127	78	0.15	0.22	37
Day 4	121	0.13	0.21	64	32	131	70	0.16	0.24	32

ii. Water Boiling Test:

One liter of water was boiled on each cooker on three different days the time taken for each of the cookers to boil the water was measured each day, the water temperature (twf), temperature of inner air in the cooker (taf) and the ambient temperature (tamb) was also measured at every 5 minutes interval, the result obtained is presented in Figures 1 -3

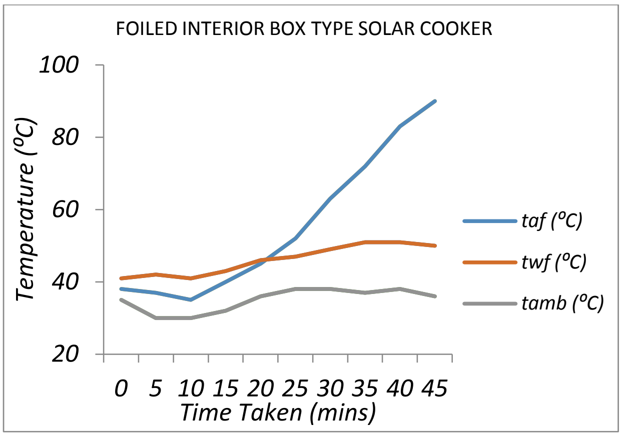

Fig. 1(a)

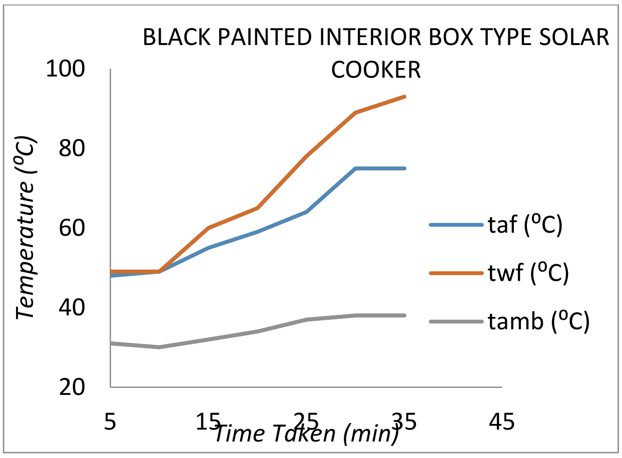

Fig. 1(b)

Fig. 1: Water Boiling Test Analysis for the Cookers at Day 1

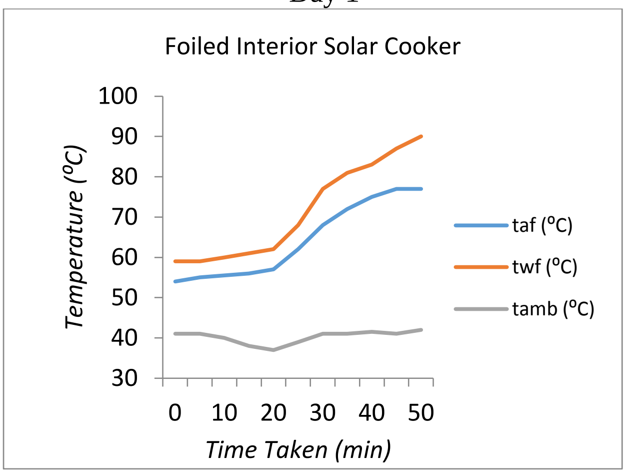

Fig. 2 (a)

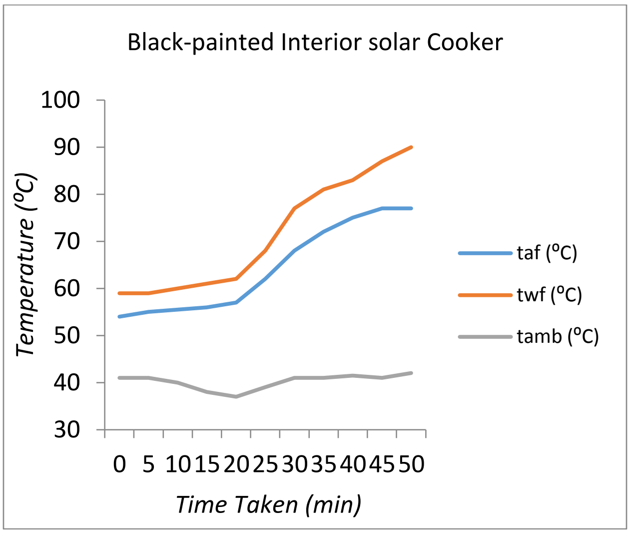

Fig. 2 (b)

Fig. 2: Water Boiling Test Analysis for the Cookers at Day 2

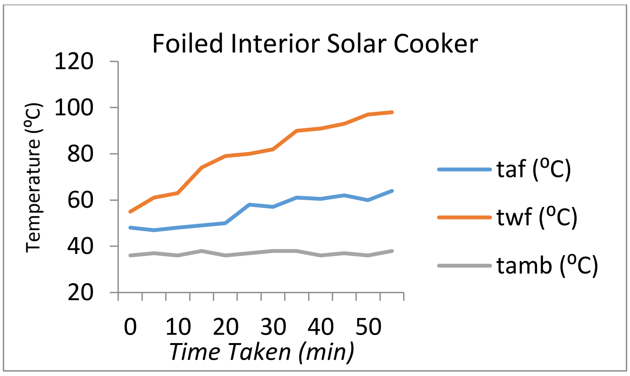

Fig. 3(a)

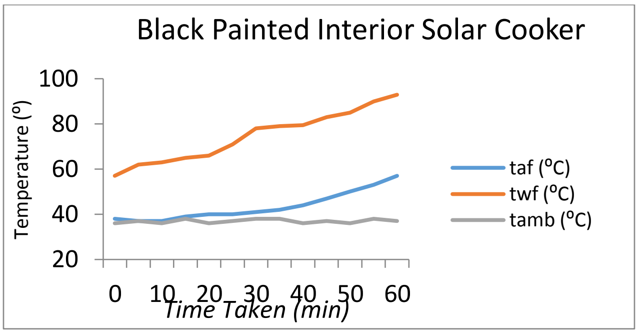

Fig. 3 (b)

Fig. 3: Water Boiling Test Analysis for the Cookers at Day 3

iii. Controlled Cooking Test:

The two cookers were used for cooking common food items on a clear sunny day; the cooking performance of the developed box type solar cookers is presented in Table 2.

Table 2: Cooking Performance of the Box type Solar Cookers

	Foiled Interior solar cooker			Black painted interior solar cooker		
Food material	**Quantity (g)**	**Mixing water (cm^3)**	**Cooking time (min)**	**Quantity (g)**	**Mixing water (cm^3)**	**Cooking time (min)**
Egg	1 piece	500	75	1 piece	500	55
Rice	400	1000	90	400	1000	80
Yam	700	1000	85	700	1000	70
Beans	500	1000	190	500	1000	180

The stagnation temperatures reached by both cookers is well over 100 °C, this signifies that the solar cookers can be used to cook most foods by boiling. However, fluctuations were observed due to irregular solar insolation, the black painted interior box type solar cooker performed better than the foiled interior box type solar cooker in terms of stagnation temperatures reached with time, the cooking time and water boiling temperature reached with time under the same prevailing weather conditions. The average solar intensity at the four days of the experiment were 716.74, 895.89, 946.12 and 1075.1 W/m2 respectively, the foiled interior cooker reached stagnation temperatures 108, 120, 124 and 121 °C respectively for the four days of the test (at ambient temperatures 34, 36, 37 and 32 °C) while the black painted solar cooker reached 117, 122, 127 and 131 °C at the same ambient temperatures for the four days. The first figure of merit was calculated from stagnation temperature test of cookers under no load, the values obtained ranged from 0.11 to 0.14 for the foiled interior solar cooker while the black painted interior solar cooker ranged from 0.12 to 0.16; these values were compared with standard values of F1 > 0.12 (BIS Standard, 1993). The lower values in the F1 must have been due to deterioration in the cookers while the high values were attributed to high optical efficiency and low heat loss (Mullick et al., 1996).

The second figure of merit (f2) calculated from both the stagnation and water boiling test ranged from 0.21 to 0.25 for foiled interior solar and 0.22 to 0.26 for the black painted interior cooker; these values were compared with standard values of F2 > 0.25 (BIS Standard, 1993), this figures are comparable with the commercial box type solar cooker reported by Mohod and Powar (2013).

The foiled interior solar cooker expended 75 mins in cooking 1 piece of egg, 90 mins in cooking 400 g of rice, 85 mins in cooking 700 g of yam and 190 mins in cooking 500 g of beans while the black painted interior cooker expended 55, 85, 70 and 180 mins for cooking the same quantities of the same food under the same prevailing weather condition.

4. CONCLUSION

The foiled interior and black-painted solar cookers provides another means of cooking energy, the cookers were able to boil water and cook different Nigerian dishes though the black painted interior cooker performs better than the foiled interior solar cooker and this is attributable to the fact that black materials are good absorbent of heat. The figures of merit obtained for both cookers indicate that the performance of the solar cookers is comparable with commercial box type solar cookers.

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