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Performance Evaluation of a Box-Type Solar oven with Reflector

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--ABSTRACT--

This paper presents the evaluation of the thermal performance of a constructed box type solar oven with reflector. The solar box oven was used to perform an experiment with reflector and without reflector in which the ambient temperature, the air temperature inside the oven, the plate temperature at the side and the bottom, of the oven were obtained. The wind speed and the solar radiation were also recorded for different days. The temperature profiles without load and with load assure its good thermal performance and the ability to boil water. The stagnation test and the water boiling test were performed during the year 2012. The efficiency of the solar oven without and with reflector was found to be about 96% and 99% respectively. Efficiency increase with decreasing temperature difference between plate temperature and ambient temperature, while it decreases with decrease in solar radiation. The result shows that the oven has a good reliability for baking and boiling water.

KEYWORDS: *Solar oven, Thermal performance, Efficiency, First Figure of Merit, Second Figure Merit.*

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I. INTRODUCTION

A significant proportion of the Nigerian population as in many other developing countries in Africa, Asia and Latin America depend on fossil fuels, biomass and firewood for baking and domestic water heating. Recent studies by Fernandez et al (2002), Bala et al (2002), Garba and Bashir (2002), Bello et al (1999) reported that in Nigeria, domestic baking, cooking and heating account for more than 70% of the energy needs of most households. There is no gain saying the fact that, conventional sources of energy for domestic baking like liquefied petroleum gas otherwise called natural gas, kerosene and electricity are characterized by irregular availability, increasing costs and some are mostly not environmentally friendly. Energy is required in all aspects of everyday life, including agriculture, drinking water, lighting, health-care services, telecommunications, and domestic and industrial activities. The trend of total reliance on finite fossil fuels for daily energy demands must change for good; therefore a collective effort is urgently needed to save the environment from climate change caused by acid rain, global warming and other ecological degradations, which have adverse consequences on the environment (Garba 2009). Solar energy was the origin of fossil fuels, which became the basis on which the Industrial Revolution was built. These conventional sources of energy, however, will not last forever, and have proven to be one of the main sources of environmental problems. Renewable energy sources, such as solar energy, cannot be depleted for all practical purposes. In contrast to fossil fuels they are clean sources of energy and do not pollute the environment during the process of power generation. It is clear that in due time renewable energies will dominate the world's energy System, due to their inherent advantages such as mitigation of climate change, generation of employment and reduction of poverty, as well as increased energy security and supply.

Solar energy is one of the main alternative renewable sources of energy crucial to our search for domestic fuel replacements. This is because; it is the source of almost all renewable and non-renewable sources of energy. Also, it is one of the cleanest, it is free from environmental hazards and it is readily available and inexhaustible. However, like the development of all other energy sources, the breakthrough of solar energy into the technological world will involve a lot of planning, organization, generation and diffusion of information as well as the provision of infrastructure or devices to harness, it is an efficient and effective means. The total solar power that is incident on the earth's surface from sun is equivalent to 1.5×10^{18} kW h annually, which is equivalent to 1.9×10^{14} ton coal equivalent (Tec). Compared to the annual world consumption of almost 10^{10} Tec, this is a very huge amount and approximately 10,000 times greater than what is consumed on the earth annually (Sunita and Prabha, 2009). On the one hand photovoltaic applications of solar energy have potential to meet electricity demand of world while on the other hand solar thermal applications also have immense

potential especially in domestic and industrial sector to meet the global thermal energy demand. Finally, the use of solar energy in solar ovens for baking can solve to some extent the challenges of energy needs for Nigeria.
This paper discusses the fabrication details of a box-type solar oven, its thermal performance and efficiency. Two important thermal parameters: first figure of merit (F_1) and second figure of merit (F_2) for the solar oven have been determined by the experimental studies. Solar cooking or baking can save time and it is also environmentally friendly.

II. MATERIALS AND METHOD

Materials

The solar oven was constructed with locally available materials. Plywood for the casing, a 2x3 reflective mirror, metal, hinges, screw, black paint, 2x3 plane glasses, caste roller, metallic pans, hanging mechanism, insulator form, and caster wheel among others. The upper surface of the absorber plate is painted black which will improve the effectiveness of turning light into heat.

Design and Construction Details : The design of the solar box oven constructed for this solar energy study was based on previous works by Garba (2009) with some modification. The modification entails the addition of booster reflector which improves the efficiency of the solar oven. The design details of the solar box oven are as follows: The casing of the oven is of plywood. It has better weather ability and life than cardboard and plywood solar ovens; it is lighter than metal body ovens and can be made locally as against fibers body ovens, which cannot be made locally. The outer dimensions of the box are 58 × 46.5 × 15.5 cm^3, which are 14-34% less than the commercially available domestic solar ovens, so the oven can be handled/transported conveniently, by senior citizens/physically weak persons. The solar ovens are with 4 wheels each for convenient movement of the ovens wheels, if so desired. An aluminum tray of dimensions 47×35.5×8.5 cm^3 and thickness 0.5 m is used as the absorbing surface. The upper surface of the absorber plate is painted black. The space between the tray and the encasement was filled with glass wool to provide thermal insulation .The top of the oven is cover with a transparent glass. A plane mirror of silicate glass of thickness 4 mm and dimensions 54.6×40.5 cm^2, hinged at the top of the oven is used as reflector. To adjust mirror angle holes are provided on both outer sides of oven.

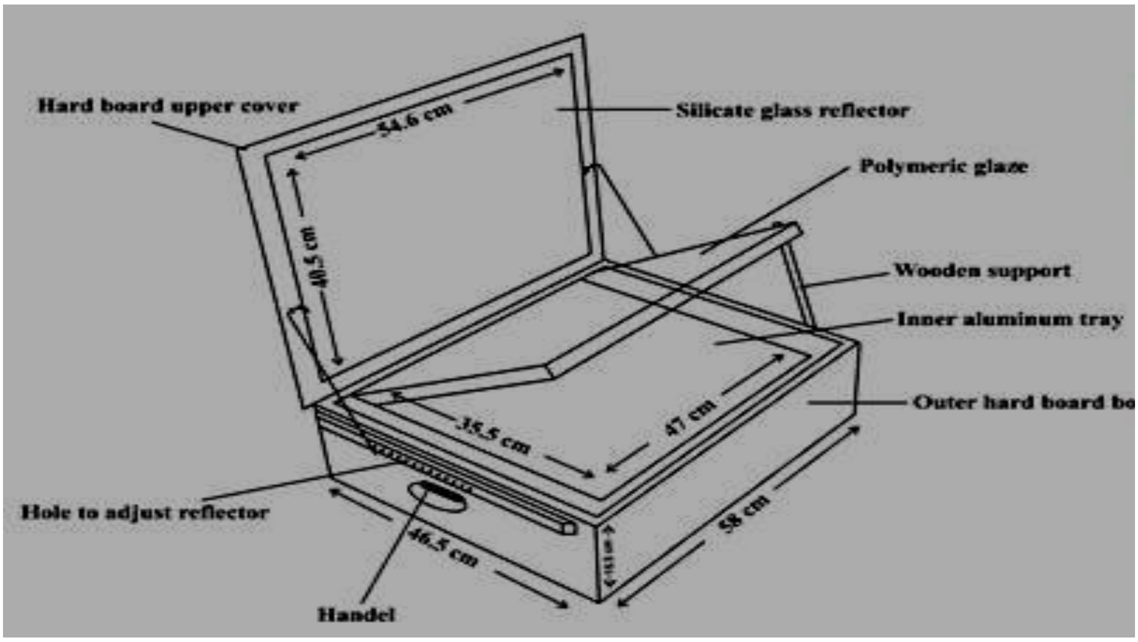

Figure 1: Schematic Diagram of the box-type solar oven.

Solar oven operate on the principles of collecting sunlight, trapping heat from that sunlight and putting the heat on the food. Solar oven collect and retain heat from the sun to provide a safe and environmentally clean method of baking food and sterilizing water.In the experimental performance evaluation test of solar box oven, the oven was positioned in an open space at the Usmanu Danfodiyo University Sokoto energy research Centre. The thermal system was placed in such a way that it was free from shadows of the adjacent building throughout the period of investigation. A thermocouple thermometer was used to measure the ambient temperature and absorber plate temperature in the box oven at different interval of 30 minutes. The experimental test of the oven started at 10:00am for the period of experiment and lasted to 14:00 GMT

Experimental arrangement : The experiments were performed and the thermal performance of a box-type solar oven was observed on the 11th December, 12th December and 13th December in the year 2012 on the field at Sokoto energy research Centre, Usmanu Danfodiyo University, Sokoto. During the experiments, the solar radiation intensity (I_s) on a horizontal surface is measured using a pyranometer, the temperatures at different point was measured with a thermocouples type of thermometer. The absorber plate, the side and bottom of the oven and the ambient temperatures are measured. The wind speed is measured by an anemometer (AM-4812). All measurements are taken at 30 minutes interval.

The thermal performance of the box solar oven system was evaluated through the application of established standards for evaluation of box type solar ovens; known as the first and second figure of merits (F_1) and (F_2) respectively.

The first figure of merit (F_1) is the stagnation test (thermal performance without water load) for box type solar oven and is giving as; the ratio of optical efficiency $F\eta o$ to overall heat loss coefficient $F_{ul}$of the cooker collector. This is represented mathematically as:

$$F_1 = \frac{F\eta o}{F_{ul}} = \frac{T_{ps} - T_{as}}{I} \qquad (1)$$

where $F\eta o$ the system optical efficiency and F_{ul} is the overall heat loss coefficient. Similarly $\mathbf{T_{ps}}$ is the stagnation plate (tray) temperature (°C), $\mathbf{T_{as}}$ average ambient temperature (°C) and **I** is the solar radiation level (W/m^2).Temperature of based plate of the oven without water load is recorded from 10:00 to 14:00 GMT and simultaneously values of insolation and ambient temperature were also measured. (See table 1) Tracking of the system is done due to the presence of reflector.

Secondly, the second figure of merit (F_2) is another formula for evaluating box type solar cooker performance through water boiling tests (Sensible heat test). The second figure of merit F_2 is related to F_1 through other parameters, and is given as:

$$F_2 = F_1(MC)_W = \frac{F_1(MC)_W}{A_\tau} In((1 - \frac{1}{F_1}\frac{(T_{w1} - T_a)}{I} / 1 \frac{1}{F_1}(\frac{T_{w2} - T_a}{I})) \qquad (2)$$

where $(MC)_w$, is the product of the mass of water and its specific heat capacity, $A\tau$ the aperture area of the box-type solar oven per the time interval during which water temperature rises from T_{W1} to T_{W2}. F_1 represents the heat exchange efficiency factor. The data's recorded during this test are given in table 2 and 3.

III. RESULTS AND DISCUSSION

Table 1: Stagnation temperature test (F_1) on 11th December 2012.

Time	Ta(°C)	Ti(°C)	Ts(°C)	Tb(°C)	I (W/m^2)	Wind Speed
10:00	39.9	45.0	51.0	68.5	887	2.9
10:30	41.1	47.9	56.8	70.8	898	2.5
11:00	42.4	50.2	60.9	75.9	871	2.2
11:30	43.6	70.5	73.9	86.7	890	2.3
12:00	44.4	79.4	83.4	89.6	905	2.7
12:30	45.4	84.6	84.4	90.2	917	3.3
1:00	45.9	88.2	86.8	98.7	919	2.6
1:30	47.0	93.1	88.5	106.0	920	3.3
2:00	49.1	95.0	91.3	110.2	929	3.4

Table 2: Thermal performance with water load (heat test) on 12th December 2012

Time	Ta(⁰C)	Ti(⁰C)	Ts(⁰C)	Tb(⁰C)	I (W/m^2)	Wind speed
10:00	31.8	44.8	35.8	45.2	726	3.3
10:30	32.7	52.8	40.6	54.8	782	3.4
11:00	35.2	55.1	56.8	67.4	789	3.0
11:30	38.6	58.4	60.2	80.6	871	2.5
12:00	39.9	62.5	65.6	89.6	896	2.4
12:30	40.8	65.6	79.4	92.8	912	2.2
1:00	42.6	79.4	81.3	96.8	917	2.0
1:30	43.6	88.2	91.5	99.1	902	2.3
2:00	44.2	93.1	93.6	101.2	886	2.1

Table 3: Thermal performance with water load (heat test) on 13th December 2012

Time	Ta(⁰C)	Ti(⁰C)	Ts(⁰C)	Tb(⁰C)	I (W/m²)	Wind speed
10:00	30.5	43.8	32.8	43.1	703	3.2
10:30	32.9	51.9	48.6	64.9	791	4.8
11:00	35.5	60.5	58.3	79.3	849	3.0
11:30	35.6	64.4	64.9	88.3	904	3.4
12:00	37.0	68.4	69.7	93.6	932	4.0
12:30	36.7	70.5	74.9	95.8	940	2.4
1:00	38.4	75.6	77.3	95.4	939	2.1
1:30	39.5	77.3	79.7	96.7	904	2.3
2:00	41.8	77.4	81.0	97.4	848	2.5

The table of result of the variations in temperatures observed on the 11th, 12th and 13th December 2012 are presented in table 1, 2 and 3. The weather was very favorable within these three days that the experiment was carried out; the days were clear and sunny. The experiment shows that temperatures continue to increase and even got to about 80°C and above. It is also observed that the plate temperature was very high reaching about 97°C. On 13th December when the insolation was 940W/m², the ambient temperature was 36.7°C. During the stagnation test it was observed that the plate temperature at the bottom of the solar oven reaches 110.2°C at 2:00pm on the 11th December. The result during the water boiling test shows that the temperatures reaches 90°C and remain high for about 1hour 30 minute. It show that solar oven may not be as fast as the conventional oven but it makes baking simple, safe and it is very convenient. The reflector increases the amount of solar radiation getting to the box as presented in table 2 and 3.It is clear that the solar box oven can bake and also cook different Nigeria dishes during the sunny periods (when the sunshine is high) of the year.

Percentage efficiency

$\frac{output\ efficiency}{input\ efficiency} \times 100\%$

Output efficiency = $\eta_o - a_1 \frac{(T_c - T_a)}{E_g} - a_2 \frac{(T_c - T_a)2}{E_g} = 0.787 - 2.6 \frac{43.1-30.5}{1000} - 0.01 \frac{(43.1-30.5)2}{1000}$

$= 0.787 - 2.6 \frac{12.6}{1000} - 0.01 \frac{(12.6)2}{1000} = 0.787 - 0.03276 - 0.0015876$

$= 0.753$

Input efficiency $= 0.787 - 2.6 \frac{(30.5-30.5)}{1000} - 0.01 \frac{(30.5-30.5)2}{1000} = 0.787$

Percentage efficiency$= \frac{0.753}{0.787} \times 100\% = 96\%$

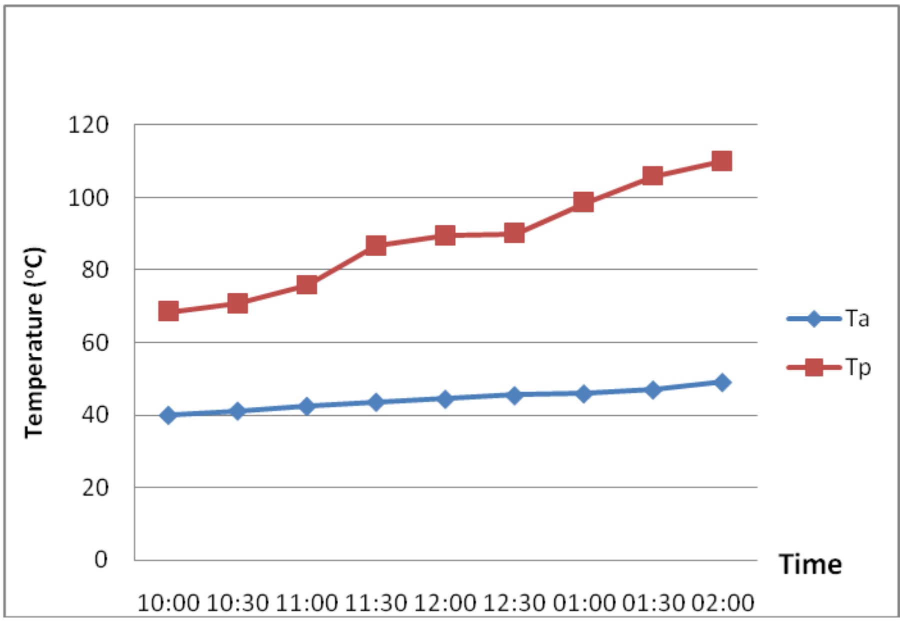

Figure 2: The temperature profile on selected day 11th December, 2012.

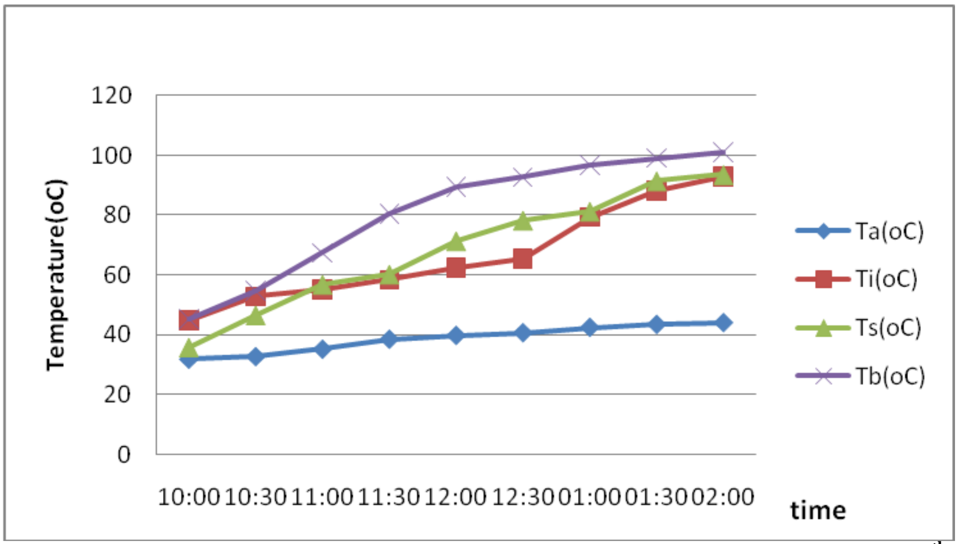

Figure 3: variation of temperature with time, with reflector and with load on selected day 12th December, 2012.

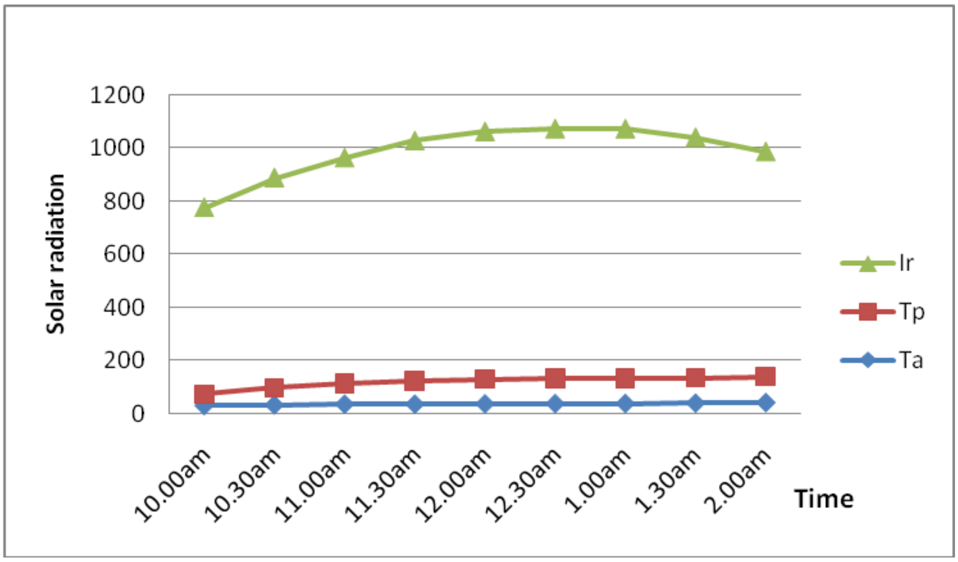

Figure 4: Result of the ambient temperature (Ta), plate temperature (Tp) and the solar radiation (Ir) with time.

IV. CONCLUSION

The solar box oven was found to be able to boil water with a temperature as high as 93°C and can even bake since the temperature of the solar oven continue to increase up to 100 °C. The efficiency was found to be 96%.The performance evaluation of the solar oven satisfied the standards for solar oven. F_1 and F_2 indicate that the oven can be used for baking on a sunny day. Indeed the use of solar oven will help in minimizing the cost of living and the use of fuel wood which is dangerous to our health and the oven is affordable.

Nomenclature

Ta = Ambient Temperature in °C
Ti = Temperature inside the oven, °C
Ts = Temperature at the side of the oven, °C
Tb = Temperature at the bottom of the oven, °C
Tp = Plate Temperature, °C
Ir = Solar Radiation w/m^2
Tc = Temperature of the collector (absorber plate), °C
Tps = The stagnation plate temperature, °C

Tas = Average ambient temperature, ^{o}C

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