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Thermal Performance Testing of Parabolic Solar Cooker Using New World Standard Procedure

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Abstract

The new world standard procedure for testing solar cookers was followed to determine thermal performance of parabolic concentrating solar cooker. The new standard sets limits for environmental conditions, specifies test procedure and performance in terms of cooking power. The standard cooking power with a good fit linear regression (R^2 = 80.256%), standard stagnation temperature of 148^0C at beam radiation of 584.1W/m^2, standard sensible heating time of 21.4 minutes, standardized unattended cooking time of 15.56 minutes and thermal efficiency of 17.5% was determined using the new standard.

Keywords: solar cooker, standard procedure, cooking power and thermal performance.

1.0 Introduction

Solar cookers are required since firewood used for cooking causes deforestation, commercial fuels are not readily available to the reach of a common man, dried cow dung and agricultural wastes used for cooking is a good fertilizer, and human resources used for collecting fuel can be diverted and used for some other useful purposes. Although a variety of solar cookers have been developed, but these are not in used as expected due mainly to incompatible with traditional cooking practices. Solar cooking presents an alternative energy source for cooking. It is a simple, safe and convenient way to cook food without consuming fuels, heating up the kitchen and polluting the environment. It is appropriate for of millions of people around the world with scare fuel and financial resource to pay for cooking fuel. Solar cookers can also be used for boiling of drinking water, providing access to safe drinking water to millions of people thus preventing waterborne illnesses. Solar cookers have many advantages, on the health, time and income of the users and on the environment. In tropical countries, the solar energy is plenty and therefore it becomes a reliable and sustainable source of energy.

The parabolic concentrating solar cooker is the only class of solar cooker that is truly suitable for frying, as the temperature at the focus can rival that of conventional electric, gas, or wood fired stoves. The solar cookers have been subjected to several types of tests to rate its performance. Mullik et al. (1987) presented a set of tests procedures and equations to assess the thermal performance of the solar cookers especially the box type cookers. Their recommendations later got adopted by Bureau of Indian Standards (BIS), and the results were expressed as factor of merit. In the recent past, Petela (2005) concentrated on exergy aspects. However, it was Funk (2000) that found a need to evolve an International Standard for testing solar cookers. The recommendations were later adopted by United States Agricultural Engineers as ASAE S580. Nandwani et al, (1997) and later Mukaro and Tinarwo (2008) have conducted tests on solar cookers and have reported the thermal performance in terms of percentage efficiency. While El Sebaii and Ibrahim (2005), Florida Solar Energy Center FSEC (2002) and McMillan and Jones (2001) have conducted tests as per ASAE S580 for box type and panel type of cookers. But it is very difficult to tabulate comparative data as many other popular types of cookers have not been subjected to standard tests. Thus there is an urgent need to evolve a comprehensive procedure to evaluate solar cookers.

It is interesting to note that while earlier researchers (Ashok and Sudhir, 2009) did consider many other aspects of solar cookers such as handling, duration of cooking time and the like, along with thermal performance, recent tests concentrated only on thermal performance. Besides, the figures obtained after the tests were presented in the form of 'Factor of merit' rather than in a format easily comprehendible by the common person. Thus the present proposal recommends a set of tests which in the words of Shaw (2002) "presenting thermal, qualitative and ergonomic data into an understandable, reproducible and rigorous testing method."

2.0 Thermal performance Testing Procedures Using New Standard

The performance of a solar cooker depends on many parameters such as climatic parameters like solar radiation, ambient temperature, wind speed etc.

A procedure for testing the solar cookers was developed based on existing international testing standards. A review of some commonly used international standards was made. They include three major testing standards for solar cookers that are commonly employed in different parts of the world. These are the American Society of Agricultural Engineers Standard (ASAE S58, 2003) (Funk, 2000), Bureau of Indian Standard Testing Method (Mullick et al, 1987) and European Committee on Solar Cooking Research Testing Standard (Shaw (2002). The procedures followed to evaluate the performance of solar cooker consist of determination of the following;

1. Cooking time for different food products,
2. Time required for a sensible heating of a known quantity of water up to the boiling point,
3. Stagnation plate temperature recorded in a test without load.

The second and third methods are better approaches (El- Sebaii, 2005), because the first method involves uncertainties due to variation in the ingredients and judgment of the observer as to when exactly the food is completely cooked. Khalifa et al, (1985) used the second method to evaluate solar cooker performance by calculating the overall thermal efficiency η_u as well as the specific t_s and characteristic boiling time t_c. The time t_s (min m^2/kg) represent the time required to boil 1 kg of water using a solar cooker of 1 m^2 aperture area. The t_c (min m^2/ kg) may be used as a parameter for making comparison between various solar cooker designs under different solar insolation levels.

Overall utilizable efficiency as discussed by Khalifa et al. (1985) for the solar cooker was calculated using the following formula:

$$\eta_u = \frac{M_f C_f \Delta T_f}{I_{av} A_c \Delta t} \quad (1)$$

Where M_f, C_f are the mass (kg) and specific heat (J/kg.K) of the cooking fluid, Δt is the time required to achieve the maximum temperature of the cooking fluid, I_{av} is the average solar intensity (W/m^2) during the time interval Δt and A_c is the concentrator area (m^2).

The specific boiling time (t_s) required to heat mass of water M_f, to boiling is expressed as;

$$t_s = \frac{\Delta t A_c}{M_f} \quad (2)$$

Alternatively,

$$t_c = \frac{t_s I_{av}}{I_0} \quad (3)$$

I_0 is the reference average solar intensity equals 700 W/m^2 (Funk, 2000).

From the measurements taken, the data was reduced to four thermal figures of merit, or standards of performance. These figures allow easy comparison of different types of solar cookers. Due to inaccuracies in temperature measurements near the boiling point of water, all tests involving water was conducted up to a maximum of 95°C. Once this temperature is reached during any test, the test was considered concluded and any data for temperatures above 95°C was be disregarded as stated in the new standard.

- *Standard Cooking Power*: This figure was taken based on the temperature change of the test load under known insolation conditions. The values are corrected to a standard horizontal insolation of 700 W/m^2. The process for calculating this figure is nearly identical to that developed by Funk et al, 2000 in ASAE S580, and is given below.

From Funk's definition, the temperature change of the water was measured over 10 minute intervals, and cooking power expressed as:

$$P = \frac{M_f C_f \left(T_{f2} - T_{f1}\right)}{600} \tag{4}$$

Where,

T_{f2} = Water temperature at the end of interval, (^{0}K)

T_{f1} = Water temperature at the beginning of interval, (^{0}K)

Equation 4 is divided by 600 because there are 600 seconds in each 10-minute interval.

Funk, (2000), also introduced the term standard cooking power normalized to 700 W/m^2 which is expressed as;

$$P_n = P\left(\frac{700}{I_0}\right) \tag{5}$$

To find the cooking power and standard cooking power, the parameters measured are, wind speed, ambient temperature, water temperature, solar radiation. According to Funk, (2000), Wind speed should be less than 1 m/s at the elevation of cooker being tested. If wind speed is 2.5 m/s for more than 10 min then test should be stopped. Ambient temperature should be in the range of 20–35^{0}C. Water temperature of the pot should be recorded in between 40 and 90 ^{0}C. Solar radiation during the experimentation should be in the range of 450–1100 W/m^2.

- *Standard Stagnation Temperature:* The stagnation temperature gives an understandable figure for the maximum possible temperature achievable by a cooker under a specific set of conditions. This test was conducted using a dry, empty cooking vessel with two thermocouple leads fixed such that they measured the air temperature roughly in the center of the cooking pot. The standard stagnation temperature is simply given by:

$$SST = \left(\frac{T_s - T_{air}}{(I_0)}\right)(700) \tag{6}$$

Measurements were conducted until values of T_s have stabilized or 2 hours have elapsed, whichever occurs first.

- *Standard Sensible Heating Time:* Perhaps more important to the average user than power and temperature, is the time taken to perform a cooking function. This figure of merit indicates how long it will take the cooker under investigation to heat a known quantity of water to 50°C above ambient temperature under a horizontal insolation of 700 W/m^2. The basic equation describing an energy balance on the thermal mass within the cooking vessel is given by:

$$t_o = \left(\frac{I \Delta T_o}{I_o \Delta T}\right) t \tag{7}$$

For any set of measured values; ΔT, t, and I it is possible to calculate the standard sensible heating time. It should be noted, however, that for ΔT values that are very high or approaching boiling point of water, the accuracy of this equation quickly breaks down. It only applies in the sensible heating region and if ΔT includes any phase change or otherwise non-linear temperature transient regions, the equation will produce inaccurate results. It is suggested that values for a ΔT of approximately 50°C be used, to ensure that the phase change region is not approached. Data for this test was taken concurrently with that for the Standard Cooking Power.

- *Unattended Cooking Time:* This test was conducted after the measurement of Standard Cooking Power and Standard Sensible Heating Time and is intended to measure how long the cooker can maintain a high temperature without being actively tracked to follow the sun. The cooker is left stationary and the temperature of the pot contents (water) measured, as with prior tests. This continues until the pot contents had decreased in temperature by 20°C from starting temperatures (i.e. the final temperature at the end of the Standard Cooking Power test). Once again this time measurement is normalized to 700 W/m^2.

$$t_{c,s} = t_c \left(\frac{I_o}{I}\right) \quad (8)$$

3.0Results and Discussions

All experiments were conducted outdoors at Centre for Industrial Studies, Abubakar Tafawa Balewa University, Bauchi – Nigeria on June and July 2010 to evaluate the thermal figures of merit. The experiments began in the morning hours and stopped when the maximum temperature the cooking fluid (water) was achieved. During all experiments global and diffuse components of solar radiation were measured using pyranometer (CM6B model, KIPP & ZONEN DELFT Holland) with calibration of 9.63 x 10^{-6} V/ Wm^2. Wind speed was taken to see it effect on the performance of the cooker using cup counter anemometer. Its accuracy was about ± 1%. Type K thermocouples were employed for the accurate measurement of the temperatures of the ambient, pot cover, absorber (cooking pot), cooking fluid and air gap (air contained in the cooking pot). The thermocouples were the 2 mm diameter stainless steel, grounded junction type. Their size was such that caused less obstruction to heat and their accuracy was ± 0.1^{o}C, when employed with the digital temperature output meter – Kane-May KM330. The model of the parabolic solar cooker is shown on figure 4.

Experimental results in determining the best cooking time revealed that the morning and evening hours when the sun angles are low, have low solar radiation intensity and hence, unsuitable for solar cooking. Between about 9.00 a.m. to 4.00 p.m., the solar intensity is high, ranging from about 700 to 1000 W/m^2, representing a suitable range for solar cooking. As the solar radiation varies from place to place and with time of the year, the best cooking time may deviate because of the effect of cloud cover. Bauchi - Nigeria is a typical location where cloud cover affects solar cooking. As expected, the effect of cloud cover was more pronounced for reflector cookers. The adopted procedure states that wind speed should not exceed 2.5 m/s for more than 10 minutes during any given test.

Cooking power and Standard cooking power from equations (4) and (5) were reduced to a single measure of performance. This was done by plotting P_n against ΔT and performing a linear regression, where ΔT refers to (T_{water}-$T_{ambient}$) recorded for each interval of time. The Standard Cooking Power was taken from this regression for a ΔT value of 50°C. The R^2 value for this regression fit was taken until a fit with R^2 of at least 0.75 was reached. The length of time taken for this test was 4 hours, beginning in the morning or the length of time taken for the pot contents to reached 95°C (according to testing procedure). This is shown in figure 1; linear regression analysis carried out has a good fit (R^2 = 80.256%), which is in agreement with that obtained by Funk, (2000). The next thermal figure of merit is standard stagnation temperature test; it is primarily of interest to the makers of solar cooking devices. By knowing the stagnation temperature of a type of cooker, more educated choices related to construction materials can be made. The standard stagnation temperature obtained using equation 6 was found to be 149.8^0C at maximum average beam radiation of $584.1W/m^2$. At minimum average beam radiation of $450W/m^2$, it was found to be 138.4^0C; this is shown on figures 2 and 3. The third thermal figure of merit is of interest to the potential users, as it is of primary importance to know how long it will take to cook meals. From equation (7), the standard sensible heating time at beam radiation of $540W/m^2$ was found to be 21.4 minutes, and at 507.7 W/m^2 it was found to be 32 minutes. From equation (8), the standardized unattended cooking time was found to be 15.56 minutes at $540W/m^2$.

Overall efficiency of 17.5% was determined under a clear weather condition at average beam radiation of $540W/m^2$.

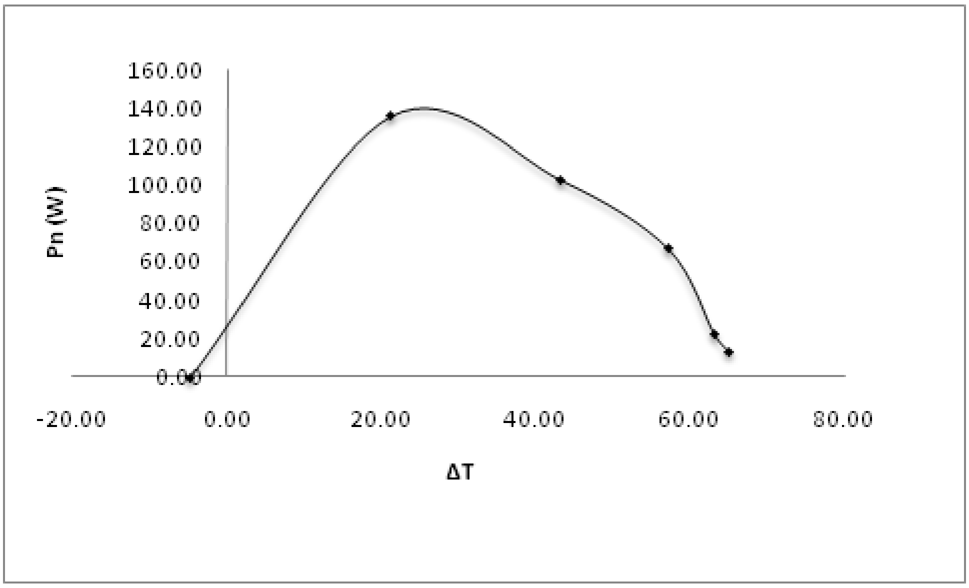


Fig. 1: Normalised cooking power Pn against ΔT. Error Mean Squ. = 540.992, Count = 5, Intercept = 186.743, Slope = -2.4005, R-square = 0.825545, Fitted Equation: Y = 186.743 – 2.4005 * X

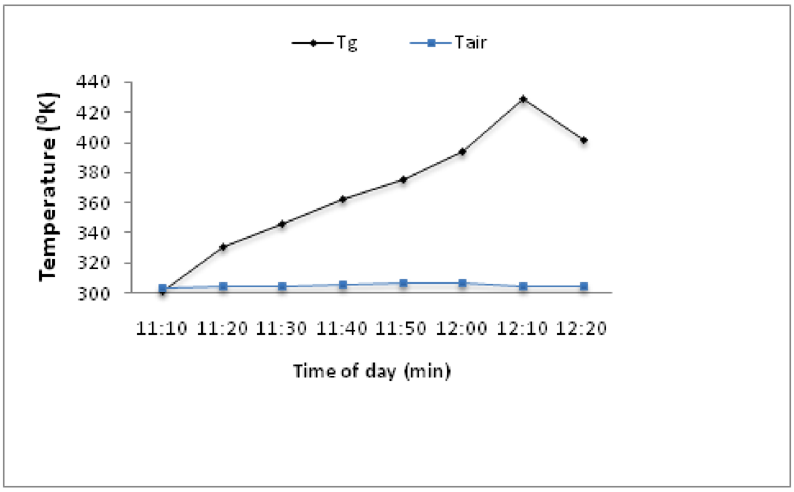


Fig. 2: Temperature versus time of day for stagnation test

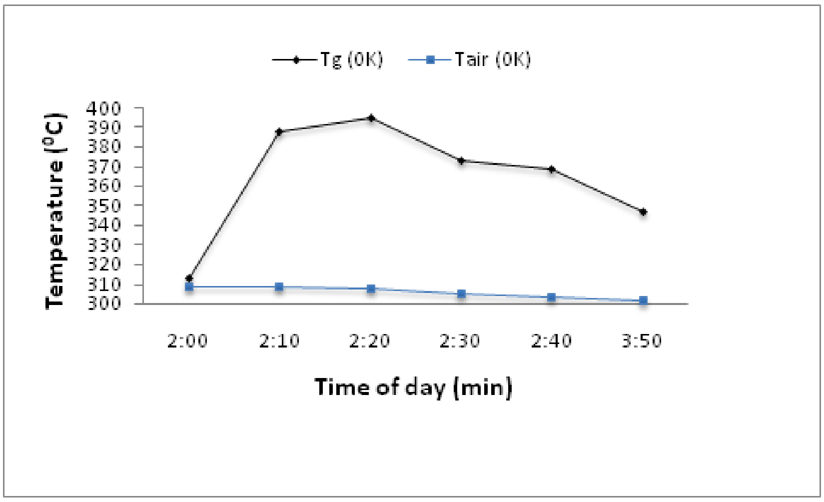
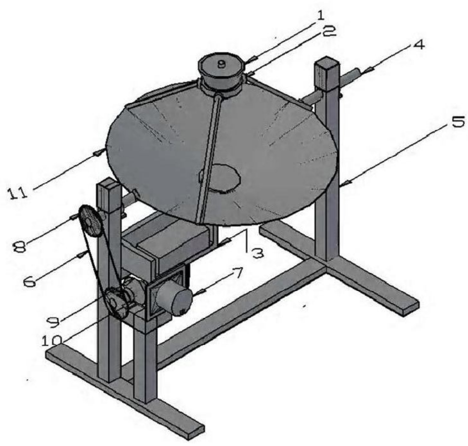
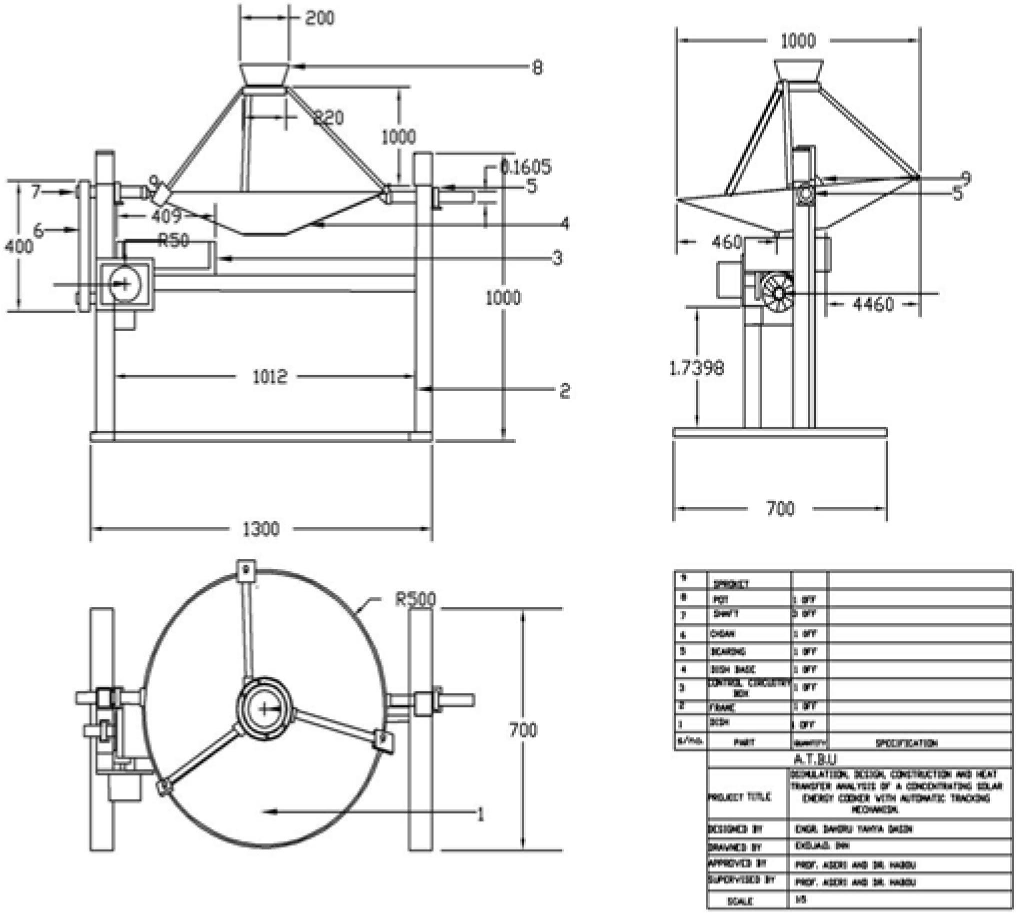


Fig. 3: Temperature versus time of day for stagnation test



S/N	PARTS
	COOKING POT
	POT HOLDER
	CONTROL CIRCUITRY BOX
	SHAFT
	FRAME
	CHAIN
	STEPPER MOTOR
	SPOROCKET
	BEVEL GEAR
	BEARING
	DISH

Fig. 4: Model of the Parabolic Solar Cooker



4.0 Conclusion

From the performance evaluation of the parabolic solar cooker, the values normalized cooking power, stagnation temperature; standard sensible heating time, unattended cooking time and cooking power at a temperature of 50^0C were within the range of parameters obtained by Funk and Larson (1998).

5.0 References

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