Performance Testing Of a Truncated Pyramid Solar Thermal Cooker

I.L. Mohammed*, U. J. Rumah*, A.T. Abdulrahim**

*Department of Mechanical Engineering, College of Engineering, Kaduna Polytechnic, Kaduna, Nigeria.
** Department of Mechanical Engineering, University of Maiduguri, Borno State, Nigeria.

ABSTRACT

This paper presents the results of performance testing of a truncated pyramid solar thermal cooker developed in the Department of Mechanical Engineering, Kaduna Polytechnic, Kaduna, Nigeria. The truncated pyramidal geometry concentrates the incident solar energy radiations towards the absorber placed at the bottom, and the glass glazing material at the top facilitates the trapping of energy inside the cooker. During testing, the highest plate stagnation temperature achieved, under no-load condition and reflector covered with black cloth, was 145 ^oC. In full-load condition the temperature of 5.2 kg of water inside the cooker rose from 60 ^oC to 90 ^oC in 72 minutes. The First Figure of Merit, F_1, was calculated to be 0.120 and the Second Figure of Merit, F_2, was found to be 0.410, thus meeting the standard prescribed by the Bureau of Indian Standards for box-type solar cookers. The relatively high absorber plate temperature developed during testing demonstrates that the cooker can be used for all the four major methods of cooking, viz: boiling/ steaming, baking, roasting/grilling, and frying (of eggs).

***Keywords* –** Cooker, performance, pyramid, solar, testing, thermal, truncated

I. INTRODUCTION

Cooking with energy from the sun is an old concept. There are many landmarks in the history of the design and application of solar cookers. The first reported solar cooker application worldwide was by a Swiss, Nicholas de Saussure (1740 – 1799) who built a black insulated box cooker with several glass covers. Even without reflectors, he reported to have successfully cook fruits at that time reaching a temperature of 88 ^oC [1]. Over the years de Saussure and others focused their cooker design work on variations on shape, size, sidings, glazings, insulations, reflectors, and the composition and reflectance of the surfaces. Today there are over 60 major designs and more than hundreds of variations [2], [3]. Increasing awareness of the growing global need for alternative cooking fuels has resulted in an expansion of solar cooker research and development.

For improving the thermal performance of solar collectors, Tiwari and Yadav [4], as cited by Abed [5], developed a Bottom-loading solar thermal cooker. Such a design ensures reduction of heat loss due to escape of hot gases when cookers are opened for intermediate operations of cooking. Aman [6] analysed the plate temperature of a box-type cooker, augmented by a booster mirror, as a function of properties of material phase change and melt depth. Mullick et al [7] developed method of evaluating box-type solar cookers using two figures of merit. Hence a method of cross comparison of different models became available; single cooker design could also be evaluated for their thermal capability and accuracy. Mullick et al [8] also conducted experiments to study the effect of the number of pots, and the load, on the Second Figure of Merit. Funk and Larson [9] and Funk [10] developed parametric models for testing box-type and paraboloidal-type cookers, and they tested several types of commercially available cookers.

This paper discusses the thermal performance of a Truncated Pyramid Solar Thermal Cooker (TPSTC) using test procedures described by the Bureau of Indian Standards [11], [12].

Solar cookers are divided into four main categories [13]:

(i) box cookers (ii) concentrator cookers (iii) solar ovens, and (iv) indirect solar cookers. The TPSTC is a hybrid cooker, in the sense that it is a box cooker as well as a concentrator cooker.

II. DESCRIPTION OF SOME PHYSICAL AND OPTICAL PROPERTIES OF THE TPSTC

The pictorial view of the TPSTC is shown in Fig. 1. The casing of the cooker is of mild steel sheet, which has better weatherproof ability and longer lifespan than cardboard or hardboard solar cookers. The overall outer dimensions of the box are 89 cm length (*l*) ***x*** 84 cm breath (*b*) ***x*** 70 cm height (*h*). A mild steel sheet of dimensions 52 cm (*l*) ***x*** 46 cm (*b*) and thickness 2 mm is used as the absorbing surface. The upper surface of the absorber plate is painted black. A single piece of transparent glass of dimensions 83 cm (*l*) ***x*** 78 cm (*b*) and thickness 2 mm is used as the glazing material. The distance between the inner surface of the glazing and upper surface of the absorber is 65 cm. The cooking chamber is accessed through a door of dimensions 30 cm (*l*) ***x*** 37 cm (*h*) situated on the front side of the cooker. The sidewalls of the cooking chamber are made from silver-coated, highly reflective glass material of thickness 2 mm. The sidewalls are separated from the outer casing by 27mm – thick insulation made of cotton. The absorber is also well insulated with cotton, before being covered by the outer casing. Two plane glass mirrors of total length 86 cm and height 81 cm, fixed in metal frame of mild steel sheet, serve as a reflector as well as a cover for the sing le glazed top. The entire body of the box is mounted on four wheels so that the cooker can be handled/transported conveniently.

Figure 1: Photograph of the TPSTC

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. Due to the geometry of the design, solar rays impinging on the inner sidewalls are 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. The booster reflector, set on top of the back side of the cooker, captures stray solar radiations and reflects them through the aperture of the cooker to heat the shaded parts of front sidewall and absorber surface.

III. FIRST AND SECOND FIGURES OF MERIT

For the evaluation of thermal performance of solar cookers, and to compare the performance of different solar cookers, standard test procedure has been described by the Bureau of Indian Standards [11], [12] which has been further revised by Mullick [14]. The test procedure provides performance characteristics of solar cookers, more or less independent of climatic variables. There are two thermal performance parameters called figures of merit (F_1 and F_2) associated with testing box-type solar cookers as per BIS. The First Figure of Merit, F_1, is determined from a stagnation test under no-load condition while the Second Figure of Merit, F_2, is determined from test under full-load condition, taking water as the load.

III.1 FIRST FIGURE OF MERIT (F_1)

The First Figure of Merit, F_1, is defined as the ratio of optical efficiency, η_o, to the overall heat loss coefficient, U_L. it is mathematically defined as:

$$F_1 = \frac{\eta_o}{U_L} \quad (1)$$

Experimentally,

$$F_1 = \frac{T_{ps} - T_{as}}{H_s} \quad (2)$$

Where T_{ps} is the plate stagnation temperature (^oC), T_{as} is the ambient temperature at stagnation (^oC), and H_s is the solar radiation intensity at stagnation (W/m^2).

The stagnation (steady state) condition is defined as the 10-minute period when

(i) variation in absorber plate temperature is less than $\pm 1\ ^oC$.

(ii) variation in solar radiation is $\pm$ 20 W/m^2.

(iii) variation in ambient temperature is $\pm$ 0.2 ^oC.

The permissible solar radiation condition during testing is that it should always be greater than 600 W/m^2.

III.2 SECOND FIGURE OF MERIT (F_2)

The Second Figure of Merit, F_2, takes into account the heat exchange efficiency of cookers and is obtained through the sensible heating of specified load of water (8 kg/m^2 of aperture area). F_2 is evaluated through the following expression:

$$F_2 = \frac{F_1 (M_w C_w)}{A\tau} \ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - T_a}{H}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - T_a}{H}\right)} \right] \quad (3)$$

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 ($\equiv$ 60 ^oC), T_{w2} is the final temperature of water ($\equiv$ 90 ^oC), 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.

IV. EXPERIMENTAL PROCEDURES

The stagnation test was conducted by placing the empty cooker on a leveled horizontal ground with the glass mirror reflector covered with black cloth. The orientation of the cooker towards the sun was adjusted using the four wheels so that maximum solar radiation intensity was received at the aperture. The temperature of centre of the absorber plate was measured continuously using a thermocouple probe with analogue temperature indicator (0 ^oC – 250 ^oC). The ambient temperature was measured using a mercury-in-glass thermometer while the solar radiation intensity was measured using a pyranometer/solarimeter (LI-18 Radiation Indicator). All measurements were made at intervals of 5 minutes. The orientation of the cooker was adjusted after every 40 minutes to keep track of the sun, until stagnation condition was achieved.

For the full load test, 5.2 kg of water was equally divided and put in two black-painted, identical aluminium pots each of mass 0.2 kg. The two pots containing the water were placed inside the cooker and the glass mirror reflector was covered with black cloth. The temperature probe of the thermocouple was placed in one of the cooking pots with the measuring tip submerged in the water. The temperature probe lead was sealed where it left the pot and the cooker. Then the entire solar cooker was placed in the sun and orientated to receive maximum solar radiation to heat the water contents of the pots. The ambient temperature, water temperature, and solar radiation intensity were measured at intervals of 5 minutes throughout the test. The orientation was adjusted after every 40 minutes. The data recording was continued until the water temperature exceeded 95 ^oC. Initial and final temperature/time data pairs were chosen as 60 ^oC and 90 ^oC respectively. The average ambient temperature and the average solar radiation intensity over the time corresponding to these two data points were then calculated.

V. RESULTS AND DISCUSSION

The stagnation test was conducted at Kaduna Polytechnic Kaduna (latitude 10.5^{o}N) on 23rd January, 2013. The test started at 10.55 a.m. till the maximum absorber plate temperature was reached after 2 hours 15 minutes. The summary of the result of the test is given in Table 1.

The stagnation plate temperature attained was 145 ^oC. The corresponding ambient temperature and solar radiation were 36 ^oC and 910 W/m^2 respectively. F_1 was calculated as per Eq. (2) and was found to be 0.120. This figure qualifies the TPSTC as Grade-A cooker, in accord with the criteria set by BIS.

The temperature profile of the absorber plate and ambient condition leading up to stagnation point are shown in Fig. 2. The trend of the curve shows that as time of the day progresses, plate temperature also increases (with increasing solar radiation intensity). The maximum plate temperature attained is 145 ^oC, which coincide with the stagnation temperature T_{ps}.

Table 1: Stagnation Test Result for Determination of F_1

Local Time (Hr:min)	Ambient Temperature (^oC)	Plate Temperature (^oC)	Solar Radiation (W/m^2)
10.55	31	31	650
11.00	32	48	730
11.05	33	55	750
11.10	33	60	780
11.15	34	68	800
11.20	34	75	810
11.25	34	80	810
11.30	34	87	820
11.35	34	95	830
11.40	34	98	830
11.45	34	101	840
11.50	35	105	860
11.55	35	110	865
12.00	36	112	865
12.05	36	115	870
12.10	36	118	900
12.15	36	121	900
12.20	36	123	890
12.25	36	125	880
12.30	36	127	900
12.35	36	130	900
12.40	36	133	890
12.45	36	135	890
12.50.	36	137	890
12.55	36	139	895
13.00	36	141	890
13.05	36	143	890
13.10	36	145	910
13.15	36	145	910
13.20	36	145	910

Plate temperature rises from 30 ^oC to a little over 100 ^oC in just about 50 minutes. It remains above 100 ^oC and moves up to 145 ^oC in about 1 hour 35 minutes. The temperature range (100 ^oC – 145 ^oC) maintained by the plate of the TPSTC for this length of time indicates that the cooker is suitable for applications in all the four major areas of cooking, viz: boiling/steaming, baking, roasting, and shallow-frying (of raw chicken eggs). It also indicates that the cooker can be employed, with minor modifications, as a dryer. Fig.2 also shows that during the testing period the ambient temperature increases (with increasing solar radiation intensity) as the time of day progresses.

The full-load test was conducted on 25th January, 2013. The test started at 10.45 a.m. and was completed after 2 hours 55 minutes, when the temperature of the water exceeded 95 °C. The result of the test is given in Table 2.

The result shows that it took 72 minutes to raise the temperature of the water from 60 °C to 90 °C. The average ambient temperature T_a and the average solar radiation H for the 72-minute period were found to be 34.5 °C and 914.1 W/m^2 respectively. F_2 was calculated as per Eq. (3) and was found to be 0.410, a figure above the minimum value of 0.4 set by BIS for proper assessment of solar box cookers.

The temperature profiles of the water and ambient condition during the test are shown in Fig. 3. The trend of the water- temperature curve shows that as time of day progresses water temperature also increases (with increasing solar radiation intensity), up to 13:10 p.m. when water temperature rises with downward trend in solar radiation intensity. It takes 78 minutes for the water temperature to reach 60 °C, and it takes another 97 minutes before the temperature reaches 96 °C. This latter time and the temperature range is sufficient to cook foods of soft load such as yams and potatoes. The full-load test result, combined with the stagnation test result, indicates that the cooker is capable of cooking, from cold start, 2 kg of dry and harder foods such as rice within the total time (2 hours 55 minutes) it takes the water temperature to reach 96 °C. This is in comparison to solar cooking test results reported in other works: [15], [16].

Table 2: Full-load Test Result for Determination of F_2

Local Time (Hr:min)	Ambient Temperature (°C)	Water Temperature (°C)	Solar Radiation (W/m^2)
10.45	31	31	750
10.50	31	33	780
10.55	32	36	800
11.00	32	36	850
11.05	32	37	860
11.10	32	38	740
11.15	32	39	760
11.20	33	40	770
11.25	33	42	790
11.30	33	44	750
11.35	33	49	820
11.40	33	50	835
11.45	33	52	845
11.50	34	55	855
11.55	34	58	870
12.00	34	59	870
12.03	34	60	890
12.05	34	62	880
12.10	34	65	880
12.15	34	68	885
12.20	34	70	900
12.25	34	72	890
12.30	34	74	900
12.35	34	76	925
12.40	35	79	925
12.45.	35	80	930
12.50	35	82	940
12.55	35	84	940
13.00	35	85	950
13.05	35	86	950
13.10	35	88	940
13.15	35	90	900
13.20	35	91	830
13.25	36	93	890
13.30	36	95	850
13.35	36	95	840
13.40	36	96	830

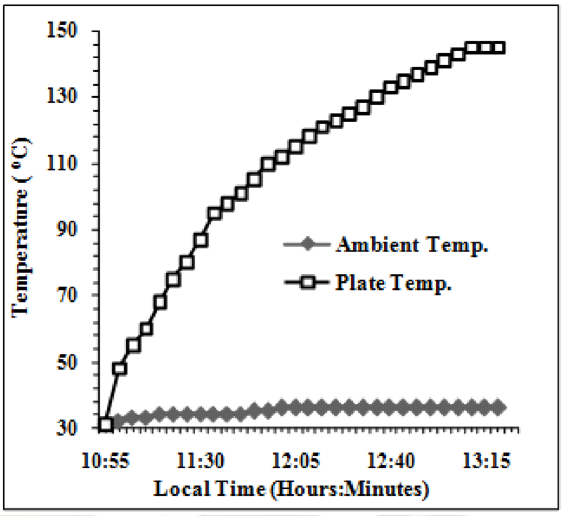

Figure 2: Temperature profiles of absorber plate and ambient condition during the stagnation test.

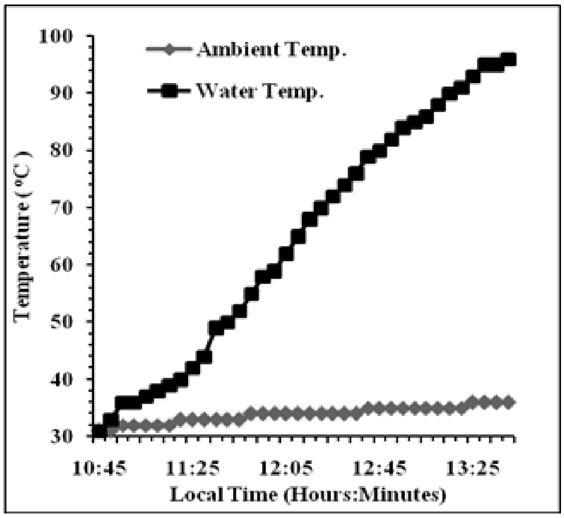

Figure 3: Temperature profiles of water and ambient condition during the full-load test.

On 22nd March, 2013 the TPSTC, with reflector exposed to solar radiation, was tested by cooking 2 kg of parboiled rice using 4.9 kg of water. The rice and water were equally divided and distributed in four identical aluminium pots painted black. The rice was well cooked in 2 hours 45 minutes, thus confirming the thermal capability of the solar cooker.

VI. CONCLUSION

The performance of the solar cooker has met the standard set by the Bureau of Indian Standards for box-type solar cookers. The First and Second Figures of Merit are reliable design and performance rating criteria for solar cookers. The stagnation and full-load test results demonstrate that the cooker can be used for methods of cooking such as boiling/ steaming, baking, roasting, and frying (of eggs); and with minor modifications, the cooker can be employed for solar drying, thereby making it a multipurpose device. The results also form a useful database for validation of theoretical models, in addition to their intrinsic value of characterising the cooker

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