Thermal Performance Evaluation of Box Type Solar Cooker using Stone Pebbles for Thermal Energy Storage

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ABSTRACT

A thermal performance of box type solar cooker with stone pebbles inside the cooker was tested with methodology described in ASAE international test standard. For the comparison, the cooker was put to test without stone pebbles, with un-coated stone pebbles and with black coated stone pebbles. The first figure of merit was found to increase with stone pebbles whereas the second figure of merit was found to decrease. However, the temperature profile of water and stone pebbles indicated that the cooked food can be kept warm for long time with stone pebbles inside the cooker. The test conducted with loading of rice resulted higher temperature around 65°C in presence of black coated stone pebbles and less than 45°C in case of test without stone pebbles. Further, rice loaded late afternoon at 3:00 pm was also cooked when black coated stone pebbles were inside the cooker.

Keywords: *Thermal Performance, Solar Cooker, Thermal Energy Storage*

1. INTRODUCTION

The adoption of solar cooker by the end users is directly influenced by their food habits. Users would accept the device, if cooking time with solar cooker matches with their meal time. Usually morning meal cannot be prepared by using solar cooker because time for morning meal is well before availability of significant solar radiation. Intensity of solar radiation peaks around noon when the solar cooker and other devices working on solar energy can yield best output. This has been one of the principal reasons why solar cookers are not widely accepted. In such circumstance, the exploration of the ways with which the adoption of solar cooker, which utilizes freely available cleaner energy, by users is indispensable.

One approach could be to store the radiant energy from the sun available around noon for cooking food later in the late afternoon such that solar cooker cooked food will be available in the evening. The solar energy can be stored in stone pebbles as sensible heat storage. The stored energy could be used to cook food during late afternoon, if not sufficient to cook food, could be used to keep warm the cooked food for long time. The cooked food during late afternoon could be used in the evening.

A box type solar cooker having mirror booster was used for the experiment. The overall dimension of the cooker is 22cm x 51cm x 51cm. The aperture area of the cooker used is 40cm x 40cm with double glazing. Dimension of the booster mirror is 46cm x 46cm.

2. TEST METHODOLOGY

The widely accepted test procedure for testing thermal performance of solar cookers is ASAE (American Society for Agricultural Engineers) standards. However, the test could not meet the requirements of radiation and wind velocity level as specified in the standard because this test was intended to study the whole day temperature profile. Thermal performance of solar cooker is evaluated by determining first figure of merit, F_1 and second figure of merit, F_2. The first figure of merit is determined by conducting the no-load test and second figure of merit is determined by load test in which known amount of water is sensibly heated in solar cooker.

The first figure of merit, F_1 is the ratio of optical efficiency to heat loss factor of the cooker, and is based on the energy balance equation as:

$$\eta_o G_s = U_L (T_p - T_a) \quad (1)$$

$$F_1 = \frac{\eta_o}{U_L} = \frac{\tau\alpha}{U_L} = \frac{(T_p - T_a)}{G_S} \quad (2)$$

The second figure of merit is determined by load test and given by the relation:

$$F_2 = \frac{F_1 (MC)_W}{A(t_2 - t_1)} \ln \left[\frac{1 - \frac{(T_{W1} - T_a)}{F_1 G}}{1 - \frac{(T_{W2} - T_a)}{F_1 G}} \right] \quad (3)$$

Experiment was carried out in the premises of Center for Energy Studies (CES), Pulchowk Campus. The following tests were carried out on the selected solar cooker:

- At first, solar cooker was put to test for no-load test without stone pebbles
- The solar cooker was experimented for load test. In load test, the cooker was loaded with three cooking utensils each containing 400g of water.
- In next step, the no-load test was again carried out but the cooker was filled with 7.5kg of stone pebbles without black coating in it.
- With stone pebbles without black coating in the cooker, the load test was also carried out.
- Stone pebbles were coated with black paint, and no-load test and load test were again carried out.

In all of the experiment mentioned above, the temperature profile in the cooker was noted throughout the day, since the beginning till sunset.

During the experiment, solar radiation intensity on horizontal surface and on the surface normal to the beam radiation was recorded. In no load test, temperature of absorber plate inside cooker was recorded. While in load test, the temperature of water in the cooking utensils was recorded. The ambient temperature was also measured in all the experiment. All of the parameters were measured at the interval of thirty minutes.

3. RESULTS AND DISCUSSION

The test on solar box type cooker was carried out in different days of February and March 2007. During the experiment, absorber plate temperature of cooker, ambient air temperature, water temperature, stone pebble temperature and solar radiation were recorded. The stone pebbles for the experiment were colleted from a local river. The mass of stone pebbles used for the testing were 7.5kg.

The first figure of merit (F_1) was calculated for all of the no-load tests and second figure of merit (F_2) was carried out for all of the load tests. Values of F_1 and F_2 obtained form different tests are given in table1. As can been seen from the table1, the first figure of merit is higher for cooker with stone pebbles. Further, this figure is higher for test carried out with black coated stone pebbles than that for without black coating. The second figure of merit is inversely related with the time for raising temperature of water. Due to the absorption of solar energy by stone pebbles during initial period, the time required to raise the temperature of water increased considerably thereby the value obtained is much lower for test with stone pebbles than without stone pebbles (see table1).

Table1 First and second figure of merits for different tests

Type of tests	**F_1 (no-load test)**	**F_2 (load test)**
Without stone pebbles	0.19	0.55
With stone pebbles but not black coated	0.21	0.23
With black coated stone pebbles	0.23	0.27

The results of no-load test without stone pebbles, with stone pebbles but not coated with black paint and with black coated stone pebbles are shown in figures 1, 2 and 3 respectively. The figures clearly indicate that the temperature obtained is higher for the test without stone pebbles. But the temperature increase is sharp and drops near to ambient temperature soon after the sun set. Also the value of temperature peaks when intensity of solar radiation is highest for the day. In case of test with stone pebbles, the more flat nature of temperature profile is obtained indicating storage of thermal energy in stone pebbles. The time of highest temperature lags by sometime with the highest intensity of solar radiation. Further, the remarkable difference can be seen in temperature profile obtained with and without black coating in stone pebbles. The maximum temperature obtained is almost 20% higher in case of black coated stone pebbles as compared to without black coating. Also in no-load test with black coated stone pebbles, maximum temperature achieved is close to that obtained without stone pebbles with additional advantage of storage of significant amount of heat in pebbles that could be utilized to maintain higher temperature for prolong time even after the sunset. At 6:30 pm, the temperature falls down near to ambient temperature in case of test without stone pebbles while it is around 50°C in test with uncoated stone pebbles and close to 60°C in case of test with black coated stone pebbles. The temperature profile shows that the cooked food during day time can be kept warm above 50°C approximately up to 7:30 pm in the evening.

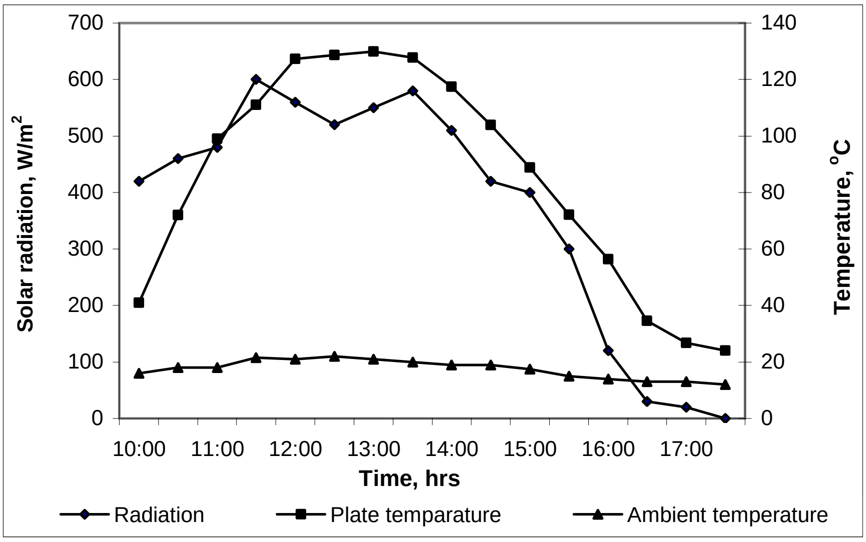

Fig. 1 Temperature profile of plate without stone pebbles during no-load test (18/02/07)

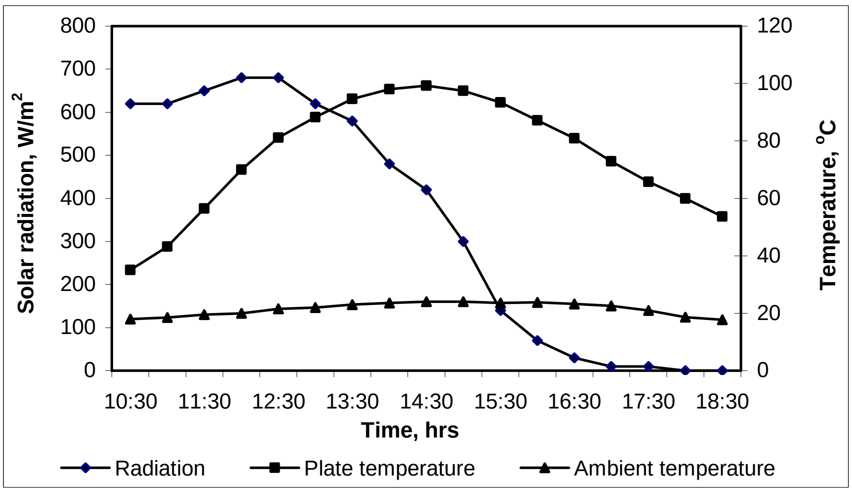

Fig. 2 Temperature profile of stone pebbles without black coating in no-load test (11/03/07)

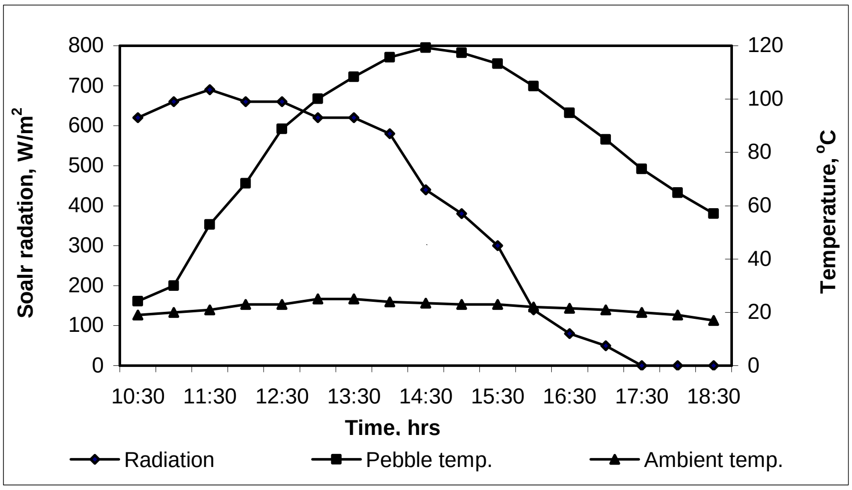

Fig. 3 Temperature profile of black coated stone pebbles in no-load test (19/03/07)

In load test, the cooker were loaded with 1.2 kg of water for all of the three tests namely without stone pebbles, with un-coated stone pebbles and with black coated stone pebbles. The nature of water temperature profile for three tests is given in following figures (figures 4, 5 and 6). Again the peak temperature occurs earlier in test without pebbles following peak solar radiation for the day whereas peak temperature occurs in test with stone pebbles little later due to energy absorption by pebbles. But the value of temperature reached is almost same, close to or equal to boiling point of water in all of three tests. The temperature of water falls at faster rate in case of test without stone pebbles reaching to about 40°C at 6:00 pm. The same remains higher than 65°C in case of test with pebbles still holding significant amount of heat in pebbles. The results show that the loading of food to be cooked can be delayed so that cooked food has to be left lesser time if food is intended for the evening meal.

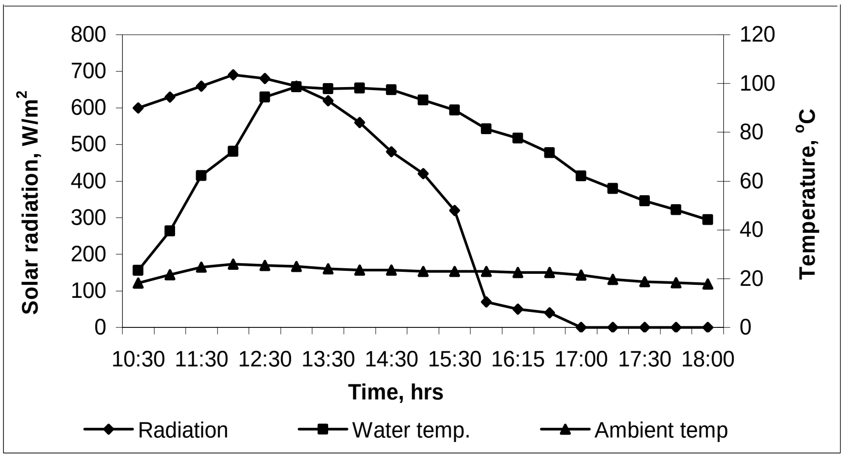

Fig. 4 Temperature profile of water without stone pebbles in load-test (04/03/07)

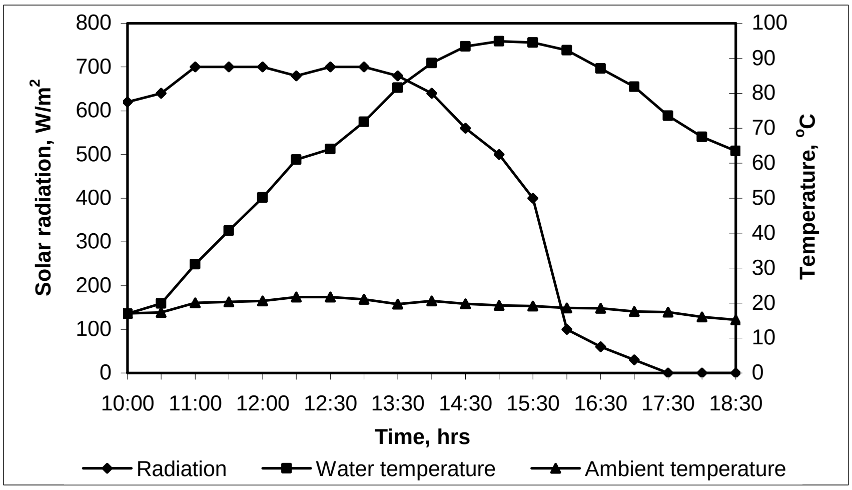

Fig. 5 Temperature profile of water for load-test with stone pebbles without black coating (16/03/07)

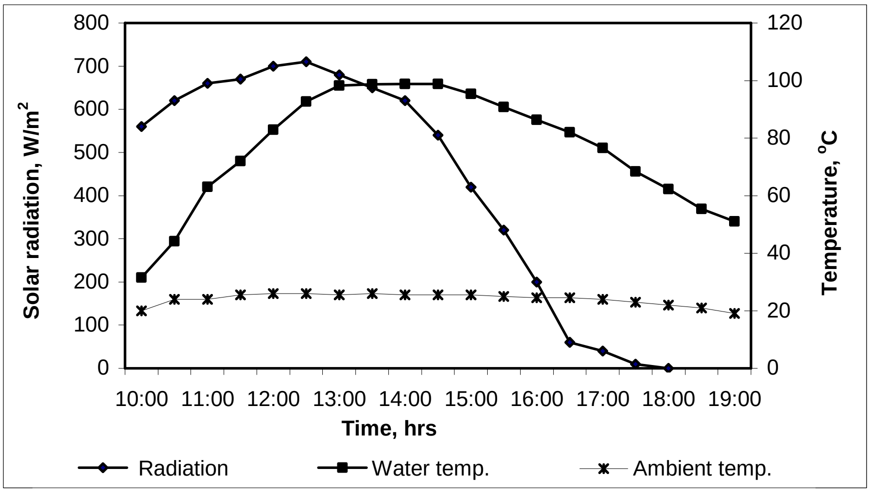

Fig. 6 Temperature profile of water in load test with black coated stone pebbles (23/03/07)

In loads test with black coated stone pebbles, stone pebble temperature was also measured. The maximum temperature of stone pebbles reached was about 99°C. The heat energy available for warming the food material inside the cooker is about 338 kJ, if acceptable lower temperature is assumed to be 50°C. The amount of energy is equivalent to energy that can raise 1.2 kg of water at 25°C to about 92°C.

The cooker was put to test with loading of rice too. Altogether 500gm of rice was cooked in a day, two third of which is loaded in the morning and remaining one third was loaded at 1:30 pm. The temperature available inside the cooker at 6:30 pm in the evening is around 60°C with black coated stone pebbles while it is around 45°C without stone pebbles in the cooker. In other test, with black coated stone pebbles, the cooker was loaded with rice at late afternoon around 3:00 pm. The cooking utensils with rice were unloaded at 7:30 pm. The rice was found to cook and still holding temperature of 54°C due to thermal energy trapped in black coated stone pebbles during day time. But the rice did not cook without stone pebbles when loaded at 3:00 pm.

4. CONCLUSION

The first figure of merit is higher when cooker is loaded with stone pebbles indicating decreased heat loss. Further this figure is found larger for the test with black coated stone pebbles. However, the second figure of merit is found to be smaller for the test with stone pebbles which depicts the slower rate of increase of temperature. This fact is, however, advantageous when keeping food for long time is concerned. The experimental results of both no-load test and load test shows that with stone pebbles inside the cooker, the time for cooking food can be delayed by considerable amount of time about two hour after the noon, thus making the cooker suitable for evening meal at about 7:00 to 7:30 pm.

Recommendation

The research work with bigger size of box type solar cooker with mirror reflector for people more than fifty should be tested and the findings be disseminated to all the stakeholders.

Nomenclature

A	Aperture area of the cooker of cover plate (m^2)
C_w	Specific heat of the water (J/kg°C)
F_1	First figure of merit from stagnation test (m^{2}° C/W)
F_2	Second figure of merit
G	Average global solar radiation over time period $t_2 - t_1$ (W/m^2)
G_S	Global solar radiation during steady state (W/m^2)
M_w	Mass of water (kg)
T_a	Average air temperature over time period $t_2 - t_1$ (°C)
T_P	Plate temperature at stagnation (°C)
T_w	Water Temperature (°C)
T_{w1}	Lower value of water temperature for evaluating the F_2 (°C)
T_{W2}	Upper value of water temperature for evaluating the F_2 (°C)
$(t_2 - t_1)$	Time taken for heating from Tw_1 to T_{W2} (seconds)
U_L	Heat loss coefficient of the cooker (W/m^2°C)
η_o	Optical Efficiency
τ	Transmissvity of glazing
α	Absorptivity of absorber plate

References

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ASAE Standard: ASAE X580 (Draft prepared for Solar Energy Committee SE-414 by Paul Funk on 25/07/2001)

Testing and Reporting Solar Cooker Performance

> Developed by the Test Standards Committee at the Third World Conference on Solar Cooking (Coimbatore, Tamil Nadu, India, 9 January 1997); editorial revisions November 1998 and July 1999; revised March 2001 (following the Third Latin American Congress on Solar Cookers, La Ceiba, Atlintico, Honduras); edited and submitted for approval to Solar Energy Committee SE-414 (ASAE 94th Annual International Meeting, Sacramento, California, USA) 31 July 2001.

SECTION 1 — PURPOSE

1.1 This Standard is intended to promote uniformity and consistency in the terms and units used to describe, test, rate and evaluate solar cookers, solar cooker components, and solar cooker operation.

1.2 This Standard is intended to provide a common format by which researchers can publish results.

1.3 This Standard is intended to provide a single measure of performance for consumers to use when selecting a solar cooker.

SECTION 2 — SCOPE

2.1 This Standard specifies test conditions, instrumentation, and procedures to assure uniformity and consistency of results.

2.2 Within the scope of this Standard a solar cooker shall be understood to include the cooking vessel(s) together with associated supporting and heat transfer and heat retention surfaces, heat storage and transfer media and associated pumps and controls, all light transmitting and light reflecting surfaces, and all associated adjustments, supports, and solar locating and tracking mechanisms as may be integral parts of a solar cooker.

SECTION 3 — COMPLIANCE DEFINITIONS

3.1 Compliance definitions. The accepted definitions of “shall,” “should” and “approved,” as included in this Standard, are:

3.1.1 “Shall” is intended to indicate requirements.

3.1.2 “Should” is intended to indicate recommendations, or that which is advised but not required.

3.1.3 “Approved” or “approval” refers to listing by a nationally recognized testing laboratory or agency.

SECTION 4 — GENERAL

4.1 This Standard specifies that test results be presented as cooking power, in Watts, normalized for ambient conditions, relative to the temperature difference between cooker contents and ambient air, both as a plot and as a regression equation for no less than 30 observations.

4.2 This Standard specifies that cooking power be presented as a single number found from the above equation for a temperature difference of 50 C.

SECTION 5 — UNCONTROLLED (WEATHER) VARIABLES

5.1 Wind. Tests shall be conducted when wind is less than 1.0 m/s at the elevation of the cooker being tested. Should wind exceed 2.5 m/s for more that ten minutes, discard that test data. If a wind shelter is required, it should be designed so as to not interfere with incoming total radiation.

5.2 Ambient temperature. Tests should be conducted when ambient temperatures are between 20 and 35ºC.

5.3 Water temperature. Test data shall only be recorded while cooking vessel contents (water) is at temperatures between 5 ºC above ambient and 5 ºC below local boiling temperature.

5.4 Insolation. Available solar energy shall be measured in the plane perpendicular to direct beam radiation (the maximum reading) using a radiation pyranometer. Variation in measured insolation greater than 100 W/m^2 during a ten-minute interval, or readings below 450 W/m^2 or above 1100 W/m^2 during the test shall render the test invalid.

5.5 Solar altitude and azimuth angle. Tests should be conducted between 10:00 and 14:00 solar time. Exceptions necessitated by solar variability or ambient temperature shall be specially noted.

SECTION 6 —CONTROLLED (COOKER) VARIABLES

6.1 Loading. Cookers shall have 7.0 kg potable water/m^2 intercept area distributed evenly between the cooking vessels supplied with the cooker. If no cooking vessels are provided, inexpensive aluminum pots painted black shall be used.

> **6.1.1 Intercept area.** Intercept area is defined as the sum of the reflector and aperture areas projected onto the plane perpendicular to direct beam radiation (Figure 1). As this quantity varies with latitude, date and time, the average beam radiation zenith angle should be calculated for the test period, and the cooker rotated in the horizontal plane (solar tracking) to compensate for azimuth angle changes.

6.2 Tracking. Azimuth angle tracking frequency should be appropriate to the cooker's acceptance angle. Box-type cookers typically require adjustment every 15 to 30 minutes or when shadows appear on the absorber plate. Parabolic-type units may require more frequent adjustment to keep the solar image focused on the cooking vessel or absorber. With box-type cookers, zenith angle tracking may be unnecessary during a two hour test conducted at mid-day. Testing should be representative of anticipated consumer habits.

6.3 Temperature sensing. Water and air temperature should be sensed with thermocouples. Each thermocouple junction should be immersed in the water in the cooking vessel(s) and secured 10mm above the bottom, at center. Thermocouple leads should pass through the cooking vessel lid inside a thermally nonconductive sleeve to protect the thermocouple wire from bending and temperature extremes. The sleeve should be secured with 100% silicone caulk to reduce water vapor loss.

6.4 Water mass. The mass of water should be determined with an electronic balance to the nearest centigram using a pre-wetted container.

SECTION 7 — TEST PROTOCOL

7.1 Recording. The average water temperature (ºC) of all cooking vessels in one cooker shall be recorded at intervals not to exceed ten minutes, and should be in units of Celsius to the nearest one tenth of a degree. Solar insolation (W/m^2) and ambient temperature (C) shall be recorded at least as frequently. Record and report the frequency of attended (manual) tracking, if any. Report azimuth angle(s) during the test. Report the test site latitude and the date(s) of testing.

7.2 Calculating cooking power. The change in water temperature for each ten-minute interval shall be multiplied by the mass, M, (Kg) and specific heat capacity, C_v, (4186 J/kgK) of the water contained in the cooking vessel(s). This product shall be divided by the 600 seconds contained in a ten-minute interval, yielding the cooking power, P, in Watts.

$$P = (T_f - T_i)MC_v/600 \quad (1)$$

where T_f is the water temperature at the end of the 10 minute interval and T_i is the temperature at the beginning.

7.3 Calculating interval averages. The average insolation, average ambient temperature, and average pot contents temperature shall be found for each interval.

7.4 Standardizing cooking power. Cooking power for each interval shall be corrected to a standard insolation of 700 W/m^2 by multiplying the observed cooking power, P, by 700 W/m^2 and dividing by the average insolation, I_{avg}, recorded during the corresponding interval.

$$P_s = P(700/ I_{avg}) \quad (2)$$

where P_s is the standardized cooking power.

7.5 Temperature difference. The ambient temperature for each interval is to be subtracted from the average cooking vessel contents temperature for each corresponding interval.

$$T_d = T_w - T_a \quad (3)$$

where T_d is the temperature difference, T_w is the cooking vessel contents (water) temperature and T_a is the ambient air temperature, all in degrees C.

7.6 Plotting. The standardized cooking power, P_s, (W) is to be plotted against the temperature difference, T_d, (ºC) for each time interval.

7.7 Regression. A linear regression of the plotted points shall be used to find the relationship between cooking power and temperature difference in terms of intercept (W) and slope (W/ºC). No fewer than 30 observations from at least three days shall be employed. The coefficient of determination (r^2) or proportion of variation in cooking power that can be attributed to the relationship found by regression should be better than 75%, and shall be reported.

7.8 Single measure of performance. The value for standardized cooking power, P_s, (W) shall be computed for a temperature difference, T_d, of 50ºC using the above determined relationship.

NOTE: for product labeling and sales literature an independent, approved laboratory using a statistically adequate number of trials shall determine this number. While this value, like the fuel economy rating of an automobile, is not a guarantee of performance, it provides consumers with a useful tool for comparison and product selection.

7.9 Reporting. A plot of the relationship between standardized cooking power and temperature difference shall be presented with the equation, following the example in Figure 2. The report shall also state the standardized cooking power at a temperature difference of 50ºC.

SECTION 8 — REFERENCES

Anonymous. (1992). Indian Standard- Solar Cooker- (3 Parts) IS 13429. Bureau of Indian Standards, New Delhi.

Funk, P.A. The International Standard Procedure for Testing Solar Cookers and Reporting Performance. ASAE Paper No. 99-4017. 5 pp. 1999

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The solar cooker design employs two mirrors in an east-west configuration, suitably fixed on a framework tilted at a certain angle with respect to the upper surface of the cooker such that all incident solar rays impinging on the mirrors within a certain specified range *hm* (acceptance half angle) with respect to the normal to the concentrator aperture plane are reflected onto the base absorber of the box of the cooker The cooker is designed with the framework of the concentrator tilted at an angle equal to the latitude of the site with a provision for seasonal tilt adjustment to keep the concentrator aligned with the direction of
the sun. The absorber, i.e. the box of the cooker is kept stationary in a horizontal position.
Performance testing of the laboratory model of the solar cooker was conducted without load and with load, at the Solar Thermal Test Facility in the Solar Energy Centre of the Ministry of Nonconventional Energy Sources. A number of tests were conducted under varying operating conditions to determine the stagnation temperature and to study the heat capacity of the cooker.

The thermal performance of a box type solar cooker is evaluated by conducting two tests,
namely, a stagnation test and a load test [9,11-[11] IS 13429 (Parts 1, 2 & 3), Indian Standard: Solar Cooker, Bureau of Indian Standards, New Delhi, 1992.]

The results of these tests provide the figures of merit of the cooker. The first test, i.e. the stagnation test (or no load test) provides the first figure of merit denoted by *F1.* The second test provides the second figure of merit denoted by *F2.* The test procedures of the thermal performance tests for determining the values of *F1* and *F2* of the box type solar cooker have been discussed in Appendix A.

The quantity of water in the pots was distributed as per Indian standards, i.e. 8 l/m2 of aperture area.

It should be noted that both the stagnation and full load tests are conducted without the booster mirror because the effective contribution of the booster mirror on the aperture of the cooker varies with the diurnal motion of the sun.

First and second figures of merit (F1 and F2) of box type solar cooker

The first figure of merit, *F1,* effectively is the ratio of optical efficiency, *go,* and overall heat loss coefficient, *UL,* of the box type solar cooker. It is obtained by keeping the solar cooker in the sun without pots in the morning, and allowing the plate temperature to rise gradually. The plate temperature, ambient temperature and solar radiation are measured, periodically. Soon after solar noon, the plate temperature becomes quasi-steady and the stagnation temperature is achieved. *F1* is, thus, calculated using the following equation:

$$F = (\eta_o/U_L) = (T_{ps} - T_{as})/ H_s$$

where *Tps, Tas,* and *Hs* represent the plate temperature, ambient air temperature and total solar radiation on the aperture plane of the box type solar cooker, respectively, at quasi-steady state (stagnation).

The test for the second figure of merit, *F2,* involves operating the solar cooker with full load (i.e. pots containing 8 l/m2). The cooker is kept in the sun in the morning and the water temperature is allowed to rise gradually until it reaches the boiling point. The water temperature, ambient temperature and solar radiation are measured and recorded simultaneously. *F2* is calculated using the following equation:

$$\frac{F_1(M_w C_w)}{\quad}\left[\frac{-\left(\frac{T_{w1}-T_a}{-}\right)}{\frac{1}{\quad}\left(\frac{T_{w2}-T_a}{-}\right)}\right]$$

where *F1* is the first figure of merit of the cooker (obtained from the stagnation test), *Mw* is the mass of water as load, Cw is the specific heat of water, *Ta* is the average temperature, *H* is the average solar radiation incident on the aperture of the cooker, *Tw1* is the initial water temperature (~60 °C), *Tw2* is the final water temperature (~90 °C), *A* is the aperture area and S is the time difference between *Tw1* and *Tw2.* It should be noted that both the stagnation and full load tests are conducted without the booster mirror because the effective contribution of the booster mirror on the aperture of the cooker varies with the diurnal motion of the sun.