DESIGN AND TESTING OF A BOX TYPE SOLAR COOKER EMPLOYING NON-TRACKING REFLECTORS

Ishan Purohit[1]
[1]Deptt. of Applied Sciences and Humanities, G. B. Pant Engineering College Uttaranchal-246001, India

[2 †], **Pallav Purohit**[2] Programme International Climate Policy, Hamburg Institute of International Economics, Germany

B. S. Negi[3]
[3]Ministry of Non-conventional Energy Sources, Lodhi Road, New Delhi – 110 003, India

ABSTRACT

A model of a box type solar cooker employing non-tracking planar reflectors has been designed and fabricated, and its thermal performance investigated experimentally. The concentrator, consisting of two planar re?ectors suitably positioned in an east–west (E-W) con?guration on an inclined framework, is mounted on the box of the cooker to re?ect incident solar radiation onto the base absorber of the cooker. The design angle of inclination of the framework is taken equal to the latitude of the location and it is adjusted seasonally. Thermal performance of the experimental solar cooker has also been compared with that of a conventional box type solar cooker whose dimensions and make are identical to the box used with the former and which was also tested simultaneously under similar solar radiation intensity and ambient conditions.

Two test standards of solar cookers have been followed for thermal performance evaluation and hence the comparative analysis. Experimental results obtained from the outdoor testing show that the laboratory model provides a stagnation temperature 15-22^{o}C higher than that of the conventional one with a booster mirror. It is also observed that the boiling point of water with the concentrator cooker is reached faster, by 50-55 minutes, than with the conventional one. The cooking power of the laboratory model has been found to be 25-50% higher than the conventional cooker in various pre-specified test conditions. It has been concluded that the solar cooker utilizing non-tracking re?ectors provides increased heat collection and faster cooking compared to the conventional box type solar cooker. The results obtained from the testing conducted at various operating conditions have been presented and discussed.

Keywords:
Non-tracking planar concentrator, Box type solar cooker, F_1 and F_2, Cooking Power

1. INTRODUCTION

Solar cooking is reckoned as a technically and commercially viable option for cooking, especially in areas with abundant solar radiation. Solar cooking offers an effective method of utilizing solar energy for meeting a considerable demand of cooking energy and, hence protecting environments. Efforts have gone into the development and testing of a variety of solar cookers and their suitability for cooking different foods [1-4]. A solar cooker for inside the kitchen has also been developed using a flat plate collector as an energy collection unit [3]. Morrison et al. [4] have utilized an evacuated type solar collector for high temperature, while Schwarzer et al. [5] utilized a double glazed solar flat plate collector. Mills [6] developed a concentrating type solar cooker using the frequently adjusted Fresnel mirror system and the seasonally adjusted mirror with an evacuated tube collector, wherein thermal storage allows the stove to be permanently placed indoors for cooking.

The box type solar cooker, however, is still the preferred option for individual family needs, mainly because of its small size and simple handling and operational requirements. There are more than half a million users of box type solar cookers in India [7]. It essentially consists of a black painted metallic trapezoidal absorber tray and is usually covered with a double glass window. The tray is kept in a metal or fiberglass outer casing. A plane reflector about the same size as the aperture area of the solar cooker is used for augmentation of solar radiation onto the aperture of solar cooker. Daily/seasonal adjustment of the reflector is required to maximize reflected irradiance onto the aperture. Here, cooking is a slow process and limited to boiling-based cooking only. In view of the above constraints, it is relevant to design a box-type solar cooker using an appropriate concentrator configuration, which can enhance the collection of solar energy without requiring daily adjustment. The design must be simple and convenient to use. Non-tracking concentrator optics [8] can be used to advantage with box type cookers by concentrating the solar radiation onto the aperture of the cooker. Field-testing carried out on different designs of solar cookers has demonstrated their ability to cook a variety of foods and acceptability of the various designs by users [9-10]. Mullick et. al. [9, 10] carried out extensive experimental studies and developed a test procedure for box type solar cookers. Recently, Funk [13] proposed an international test standard for the testing of solar cookers.

The present work aims at developing a solar cooker design which can enhance heat capacity of a box type solar cooker by augmentation of solar energy into the box for efficient cooking, utilizing non-tracking concentrator optics. The effectiveness of the booster reflector(s) associated with the conventional solar cooker critically depends upon incidence angle of the direct solar radiation, which is the function of the latitude, hour angle, azimuth and solar declination angles. To achieve maximum effect of the reflector, its daily and seasonal tracking is necessary. A laboratory model of a box type solar cooker employing a non-tracking concentrator has been designed/fabricated and its thermal performance evaluated, experimentally. The solar cooker design employs two mirrors in east-west configuration, suitably fixed on a framework tilted at a certain angle with respect to the upper surface of cooker such that all incident solar rays impinging on the mirrors within a certain specified range ?$_m$ (*acceptance-half angle*) with respect to the normal to the concentrator aperture plane are reflected onto the base absorber of box of cooker. In the laboratory model the variation of the angle of incidence of direct solar radiation in a specific season has already been taken into account by taking the effect of acceptance half angle of the non-tracking planer reflectors, hence only seasonal adjustment of the concentrator is required in the laboratory model. Testing of the laboratory model has been carried without load and with load conditions at the location of the Solar Energy Center, New Delhi (*Latitude=28^{o}N*). In order to quantify the increase in temperature achieved with the laboratory model, a conventional box type cooker of similar dimensions and make to the box used with the former was also tested simultaneously.

2. DESIGN OF NON-TRACKING CONCENTRATOR FOR LABORATORY MODEL

The optical geometry used for deriving the design of a solar cooker with lateral sides of the box of the solar cooker is presented in Figure 1. PQRS is the cross section of the cooker absorber surface, PQ and RS are the sides and QR (=D) is the width of the base absorber. The solar concentration is accomplished by positioning the reflectors on a plane to make an angle equal to the latitude of the location with the plane of the solar cooker and thereby reflect incident solar energy onto the absorber plate [14]. The width of reflectors is determined in such a way that any incident ray making an angle ?$_m$ with the normal to the base plane of concentrator and striking the extreme upper edge of the mirror, after reflection, meets the extreme edge of absorber plate on the opposite side of mirror. Hence, all the incident rays within ?$_m$, after reflection, will be intercepted within the QR portion of the absorber plate. The width of the mirror, W_1, placed on the right hand side towards the southern wall of the cooker and making an angle a$_1$ with the horizontal plane, or making an angle (a$_1$+ϕ) with the concentrator base plane is determined using simple geometrical optics as;

$$W_1 = \frac{(D'-a)\ Sin\ (2\alpha_1 + \phi - \theta_m - 90)}{Cos\ (\alpha_2 + \phi - \theta_m)} \quad (1)$$

where, $D' = D + 2d\ Cos60$ (2)

and

$$a = \frac{s\ Sin\ (120 - (2\alpha_1 + \phi - \theta_m - 90))}{Sin(2\alpha_1 + \phi - \theta_m - 90)} \quad (3)$$

where *s* is the width of the sides of the cooker. The angle of walls of the cooker tray with horizontal is taken 60^o for the purpose of the present study.

The width of the mirror, W_2, placed on the left hand side towards northern wall of the solar cooker and making an angle a$_1$ with the horizontal plane, or making an angle (a$_2$-ϕ) with the concentrator base plane is calculated as,

$$W_2 = \frac{(b - b')\ Sin\ (2\alpha_2 - 2\phi - \theta_m - 90))}{Cos\ (\alpha_2 - \phi - \theta_m)} \quad (4)$$

where, $b = \frac{D'}{Cos\phi}$ (5)

and,

$$b' = \frac{s\ Sin\ (120 - (2\alpha_2 - \phi - \theta_m - 90))}{Sin\ (2\alpha_2 - 2\phi - \theta_m - 90)} \quad (6)$$

The concentration factor (CF) of the cooker, defined as the ratio of the sum of the projections of the two mirrors on the plane of the concentrator and the width of the aperture of the cooker to the width of the absorber is calculated as,

$$CF = \frac{D' + W_1\ Cos\ (\alpha_1 + \phi) + W_2\ Cos\ (\alpha_2 - \phi)}{D} \quad (7)$$

where D' is the width of the aperture of the cooker.

The design parameters of the laboratory model and the conventional one tested are presented in Table 1. In addition, a photograph of the fabricated laboratory model solar cooker is shown in Figure 2. The concentration factor of this solar cooker is taken as 1.68.

3. THERMAL PERFORMANCE TESTING

Testing of the laboratory model of solar cooker and the other one using a booster mirror was carried out extensively, without and with load, to quantify the improvement in performance of solar cookera by using a non-tracking concentrator as per IS 13429 [13]. All test conditions are given in Table 2. The copper-constantan thermocouples were used to measure plate temperatures (T_{pc} and T_{pr}), and the ambient temperature and solar radiation was measured by RTD and a pyranometer respectively.

3.1 Stagnation Temperature Test

This test is conducted for the evaluation of first figure of merit (F_1) of solar cooker which is defined as the ratio of optical efficiency, η_o, and overall heat loss coefficient, $U_{L,sc}$, [13] i.e.

$$F_1 = \frac{\eta_o}{U_{L,sc}} = \frac{T_{ps} - T_{as}}{H_s} \quad (14)$$

where T_{ps},T_{as}, and H_s, respectively represent the tray temperature, ambient temperature and the intensity of solar radiation on the aperture of the cooker at quasi steady state (stagnation).

3.2 Thermal Load Test

This test is conducted for determination of second figure of merit of solar cooker (F_2) and can be expressed by the following expression;

$$F_2 = \frac{F_1 (M_w C_w)}{A\tau} \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - \overline{T_a}}{\overline{H}}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - \overline{T_a}}{\overline{H}}\right)} \right] \quad (15)$$

where M_w represents the mass of the water, C_w the specific heat of water, T_a the average ambient temperature, H the average solar radiation on the aperture of the cooker, T_{w1}(≅60°C), & T_{w2}(≅90°C) are initial and final water temperatures respectively, A the aperture area and τ the time interval.

In addition, the cooking power, P, is defined as the rate of useful energy available during heating period. It may be determined as a product of the change in water temperature for each interval and mass and specific heat capacity of the water contained in the cooking utensil;

$$P = (M_w C_w) \frac{(T_{wb} - T_{wa})}{\tau_{ab}} \quad (16)$$

where T_{wa} and T_{wb} represent temperatures of water respectively in at the beginning and end of time duration τ_{ab} and T_a the ambient air temperature. The cooking power, P, is plotted against (T_w-T_a) for each pre-specified time interval.

4. RESULTS & DISCUSSIONS

The variation of the widths and the concentration factors has been calculated for the two mirrors with different angles of inclinations a_1 and a_2 for a typical design case with the width of the absorber sheet D (= 0.5m), depth of the cooker d *(=0.1m)*, angle of walls of cooker tray with horizontal 60°, tilt of the concentrator (ϕ *=28°*) and ?$_{m,}$ equal to 10°. The concentration factor (C.F.) of a mirror defined as the contribution of a mirror to the concentration of solar radiation on the absorber surface of width, D, is determined by the ratio of the width of the projection of the mirror on the plane of concentrator base to the width of the absorber (i.e. W_1cos (a_1+ϕ)/D) or W_2cos (a_1-ϕ)/D). It may be observed that C.F. for the mirror W_1 first increases with increase in a_1, reaching a maximum at a_1 equal to 54°, and thereafter decreases with further increase in a_1. The CF for W_2 also increases with a_2, the rate of increase, however, starts decreasing from a_2 equals to 96°. In addition, mirrors are assumed to be specularly reflecting.

The maximum temperature attained by the first cooker, T_{pc}, is 105.8°C and that attained by second, T_{pr}, is 105.9°C under stagnation test and, hence the F_1 of the two solar cookers is obtained 0.1250 and 0.1252, respectively. Under load testing the time taken for attaining the boiling temperature (~90°C) by the above two cookers was 6320 and 6400 seconds, respectively. Therefore F_2 has been obtained for both solar cookers as 0.4048 and 0.4051, respectively. In addition, using the test method by Funk [14, 15] the cooking power, P, of the both solar cookers has been obtained 30.38 W and 30.81W respectively. The curves obtained for the determination of cooking power of both solar cookers are presented in Figures 4 and 5 respectively. The test results obtained under the load test conditions have also been compiled using the test method suggested by Funk [14]. The thermal performance parameters (*i.e. cooking power*) associated with this test method arepresented in Table 3 for both the laboratory as well as the conventional sample of solar cooker. The result shows that the cooking power of the laboratory model comes out to be higher that that of the conventional cooker, suggesting that the higher amount of energy is available in the laboratory model during cooking. Case-7 shows the best results among all the conditions specified in Table 2 and the cooking power in this condition is 64.9 W as compared to 55.7 W for the conventional cooker. In all conditions the cooking power of the laboratory model is higher that of the conventional solar cooker.

5. CONCLUSION

The experimental results obtained from the thermal performance tests carried out show that the box type solar cooker employing a non-tracking solar concentrator could provide improved heat collection and, hence efficient cooking. The cooker offers advantages of faster cooking and hence reducing the cooking time considerably. For the laboratory model, the variation of the angle of incidence of direct solar eradiation in a specific season has already been taken into account by taking the effect of acceptance half angle of the non-tracking planer reflectors; hence only seasonal adjustment of the concentrator is required. The developed model is easy to fabricate and operate, and costs only about 8-10% more than the conventional box type solar cooker.

6. REFERENCES

1. Lof, G.O.G., Solar Energy, 1963, 7(3), 125.
2. Natarajan Murthy S. and Narasingh, Solar Energy, 1985, 34, 279.
3. Khalifa A. M. A., Akyurt M. and Taha M. M. A., Applied Energy, 1986, 24, 77.
4. Morrison G. L., D. R. DL and Mills D. R. DL and Mills D. R., Proceedings of the conference of the International Solar Energy Society, 1987, 13-18.
5. Schwarzer K., Hafner B., Von Meer A. and Kings T., Proceedings of the Conference of the International Solar Energy Society, 1987, 13-18.
6. Mills, R. David and Maoyin Qin, Sun World, 1987, 11(2), 44.
7. Annual Report, Ministry of Non-conventional Energy Sources, Government of India, New Delhi 11003, 2002-2003.
8. Goshwami R. P., Sootha G. D., Negi B. S. and Zaidi Z. H., International Journal of Energy Research 16, 837.
9. Biermann E., Grupp M. and Palmer R., Solar Energy, 1999, 66 (6), 401.
10. Suharta Herliyani, Abdullah K. and Sayigh A., Solar Energy, 1998, 64(4-6), 121.
11. Mullick, S.C., Kandpal, T. C. and Sexana, A. K., Solar Energy, 1987, 39, 353.
12. IS 13429 (Parts 1, 2 & 3), ‘Indian Standard: Solar Cooker’, Bureau of Indian Standards, New Delhi (1992).
13. Funk P. A., Solar Energy, 68(1), 2000, 1-7.
14. Negi, B. S., Kumar, A. and Tripathi, T. C., SESI Journal, 11(2), 2001, 73.

TABLE 1: DESIGN PARAMETERS OF CONVENTIONAL/ LABORATORY MODEL OF SOLAR COOKERS

Design / Parameters	**Conventional Box Type Solar Cooker With Reflector**
Glazing	Double glazing [Outer: Toughened glass, 3.5 mm thick, Inner: Plane glass, 3.0 mm thick], Spacing between glasses: 20 mm
Cooking Tray	Aluminum sheet, 0.7 mm thick, Painted black with paint in dull finish
Reflector (Conventional Model)	Mirror glass, 3.5 mm thick/ 540 mm x 540 mm
Concentrator (laboratory model)	Non-tracking concentrator made up of two mirror glasses, 4 mm thick, W_1 = 460 mm x 460 mm / W_2 = 440 mm x 440 mm / $\alpha_1 = 51^o$, $\alpha_2 = 97^o$
Cover plate	Dimensions: 433 mm x 433 mm, Aperture area: 0.188 m^2
Cooking pots	Number: 3, one big and two small, Material: aluminum, Coating: Black Paint, Diameter/Height of [big pot: 202 mm/57mm], [Small pot: 150mm/50mm]

TABLE 2: VARIOUS PRE-SPECIFIED TESTING CONDITIONS FOR THERMAL PERFORMANCE EVALUATION OF BOTH SAMPLES OF SOLAR COOKERS UNDER STAGNATION AND LOAD TEST CONDITIONS

Test Condition	Abbreviation
Case – 1	Starting time 10:30 AM, Calibration Test(s); Both solar cookers are in non-tracking condition and without reflector(s).
Case – 2	Starting time 10:30 AM, Both solar cookers are in non-tracking condition.
Case – 3	Starting time 11:00 AM, Both solar cookers are in non-tracking condition.
Case – 4	Starting time 11:30 AM, Both solar cookers are in non-tracking condition.
Case – 5	Starting time 12:00 AM, Both solar cookers are in non-tracking condition.
Case – 6	Starting time 12:00 AM, The laboratory model of solar cooker stationary and the conventional cooker along with the booster mirror adjusted/tracked every half an hour.
Case – 7	Starting time 12:00 AM, The laboratory model of solar cooker tracked horizontally and the conventional cooker along with the booster mirror adjusted/tracked every half an hour
Case – 8	Starting time 12:00 AM, The laboratory model of solar cooker tilted at 24^o (ϕ - 4^o) and the conventional cooker along with the booster mirror adjusted/tracked every half an hour
Case – 9	Starting time 12:00 AM, The laboratory model of solar cooker tilted at 32^o (ϕ +4^o) and the conventional cooker along with the booster mirror adjusted/tracked every half an hour

TABLE 3: THERMAL PERFORMANCE PARAMETERS UNDER THE LOAD TEST OF TWO SOLAR COOKER AT VARIOUS PRE-SPECIFIED TEST CONDITIONS

Test Condition	Conventional Box Type Solar Cooker			Laboratory Model of Box Type Solar Cooker		
	P (Watts)	Intercept	R^2	P (Watts)	Intercept	R^2
Case – 1	30.82	-0.386	93	30.39	-0.385	93
Case – 2	35.40	-0.419	93	46.49	-0.653	95
Case – 3	40.25	-0.625	90	50.88	-0.761	92
Case – 4	44.68	-0.677	96	58.65	-0.869	93
Case – 5	46.51	-0.728	96	60.68	-0.636	93
Case – 6	55.74	-0.819	92	62.70	-0.804	94
Case – 7	55.67	-0.788	94	64.91	-0.853	91
Case – 8	41.26	-0.561	95	53.39	-0.762	92
Case – 9	46.21	-0.637	93	64.60	-0.855	93

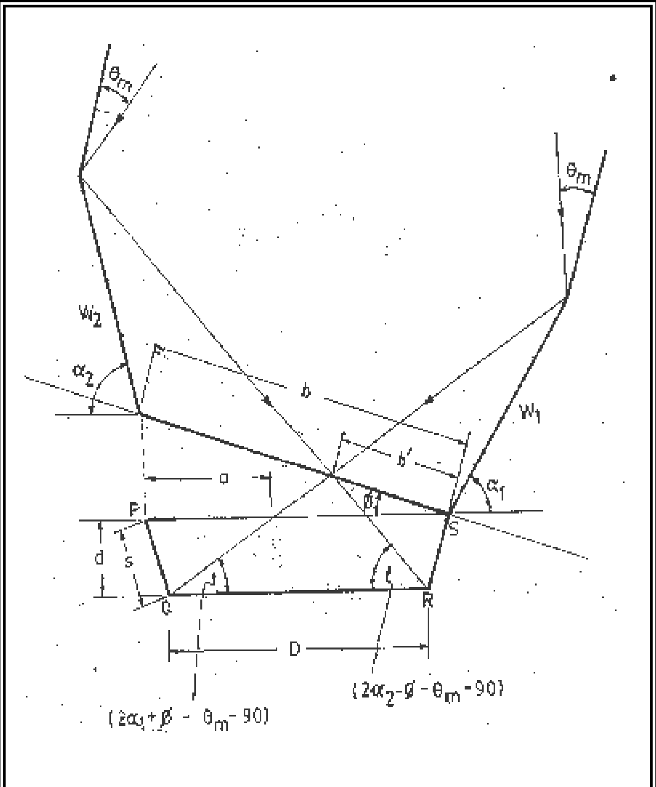

Fig-1. Schematic diagram of the laboratory model of box type solar cooker employing non-tracking

Fig-2. Photograph of the laboratory model of box type solar cooker employing non-tracking

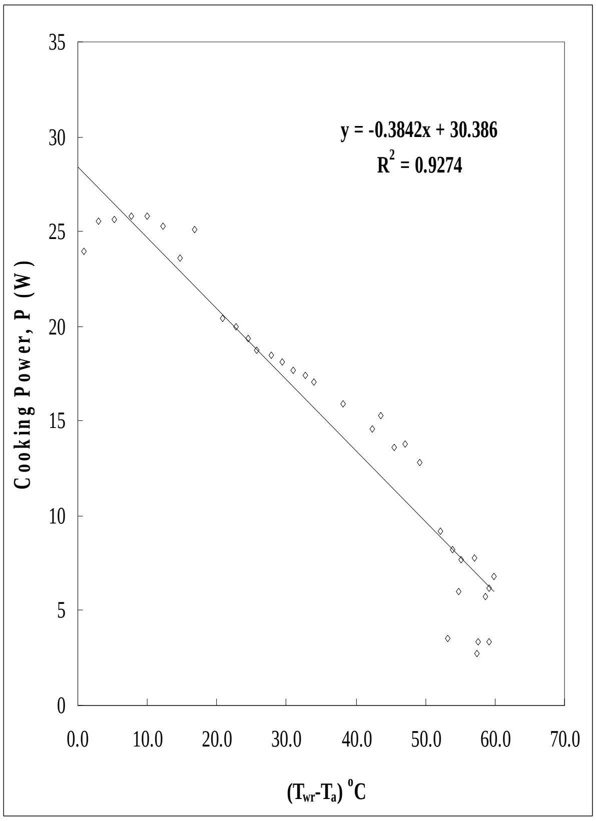

Fig-3. Cooking power of the conventional model under load test condition for Case - 1

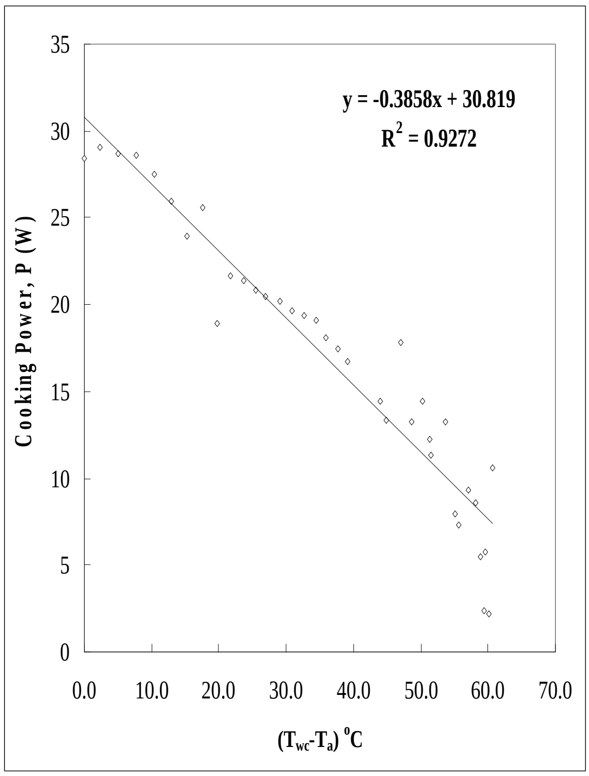

Fig-4. Cooking power of the laboratory model under load test conditions for Case-1