Extensive Experimental Studies of a Single Family Solar Cooker

Sunita Mahavar[1], Namrata Sengar[2], Manisha Verma[1] and Prabha Dashora[1]

[1]Department of Physics, University of Rajasthan, Jaipur, India
[2]Department of Pure & Applied Physics, University of Kota, Kota, India
smjpr1986@gmail.com, pdashora@yahoo.com

Abstract

This paper presents the design details and extensive experimental studies of a novel solar cooker, suitable for cooking requirements of a family of two or three persons; it is named as SFSC. Small size, good thermal performance, light weight and low cost are some important features of this cooker. The temperature profiles of various elements, without reflector, without load, and without reflector with load conditions for different days assure its good thermal performance and ability to cook two meals on a clear sunny day. The values of some essential thermal performance parameters viz. first figure of merit (F_1) and second figure of merit (F_2) suggested by Bureau of Indian Standards for a box type solar cooker are found to be 0.116 ºCm^2/W and 0.466, respectively for the developed cooker. Cooking tests of several food items, performed during 2009 confirm year round good performance of this cooker.

Keywords: *Small size solar cooker, thermal performance, figure of merit.*

1. Introduction

Energy has been universally recognized as one of the most important inputs for economic growth and human development. According to International Energy Agency 80% of the present worldwide energy use is based on fossil fuels (oil, coal and natural gases). Risks associated with their use are that they are all potentially vulnerable to adverse weather conditions of human acts. World demand for fossil fuels is expected to exceed annual production, probably within the next two decades. International economic and political crisis and conflicts can also be initiated by shortages of oil or gas. Moreover burning fossil fuels release harmful emissions such as carbon dioxide, nitrogen oxides, aerosols, etc. which have well known adverse impacts on public health, ecology, atmosphere and environment. In order to avoid harmful effects of fossil fuel consumption, replacement of its usage as much as possible with environment friendly, clean and renewable energy sources has become mandatory. Among all renewable energy sources, solar energy comes at the top of the list due to its abundance and more evenly distribution in nature [1-3].

The total 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 (tce). Compared to the annual world consumption of almost 10^{10} tce, this is a very huge amount and approximately 10,000 times greater than what is consumed on the earth annually [3]. 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 thermal energy demand of the world. Primary energy use of the household sector accounts for 15-25% in developed countries which could be higher in developing countries [4].

A judicious use of solar energy by means of solar cooking can cut down the cooking fuel expense by more than 60% and can help to overcome the harmful effects arising from the combustion of current "dirty" cooking fuels. A number of solar cookers have been designed and developed by many authors [5-10] so far, yet possibilities of improvement in the thermal performance of solar cookers which are subjected to the selection of materials for its components and design improvement, are still open.

This paper presents extensive experimental studies of a Single Family Solar Cooker (SFSC) developed by authors. In the present social scenario a large number of people are migrating from villages to cities; cities to metros; metros to cross countries and from the developing nations to the developed nations in the search of better career and life expectancies. This migration phenomenon has reduced large families into single families either young or old couple families. This has motivated authors for development of a solar cooker suitable for two or three person's cooking requirements. SFSC is appropriate for the cooking requirements of single families and has following novel features: (i) small size and light weight (ii) good thermal performance (iii) affordable cost by low or middle income group people.

The paper discusses the fabrication details of SFSC and, its year round thermal and cooking performances. Two important thermal parameters; first figure of merit (F_1) and second figure of merit (F_2) which are suggested by Bureau of Indian Standards (BIS) [11, 12] for solar cookers, have been determined by the experimental studies. The variation in the value of F_2 with the load variation is also examined and discussed. Temperature profile during food cooking and time to cook various food items through SFSC are also included in this paper.

2. Design Details of Single Family Solar Cooker (SFSC)

Recently we have made a number of lightweight low cost portable solar cookers and fixes structure building material solar cookers keeping a particular category of user in mind [13-15]. The present model is latest in the series. The design details of single family solar cooker (SFSC) are as follows:

The casing of the cooker is of hard board. It has better weather ability and life than cardboard and ply board solar cookers, it is lighter than metal body cookers and can be made locally as against fiber body cookers, 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 cookers (CSC), so the cooker can be handled/transported conveniently, by senior citizens/physically weak persons. Water proof cloth cover with six wheels, 4 in the bottom and two on side can be used to further increase the ease of transportation, if so desired. An aluminum tray of dimensions 47×35.5×8.5 cm^3 and thickness 0.35 mm is used as the absorbing surface. The upper surface of the absorber plate is painted matte-black. In this system by the use of three-layer hybrid insulation made of layers of corrugated cardboard, thermocole and crimped newspapers; weight, cost and size of the system are significantly reduced. The volume of insulation material is 30-40% less than, that in commercially available solar cooker. For the side and bottom insulations the heat loss coefficient values are found to be 0.91 and 1.05 W/m^2K, respectively, these values are comparable to heat loss coefficient values with commercial insulation (glass wool) of similar thickness. A specially designed double glaze of transparent acrylic sheets of thickness 2.75 mm with 13 mm air gap is used to trap the solar insolation. One of the reasons for selection of this glaze material is that the amount of solar radiations which is reaching to the absorber plate over the day length through polymeric glaze is 10 to 12% higher than that of plane glass glaze which has been commonly used by many authors. Moreover polymer glaze has 67% less weight as against the toughened glass glaze . A plane mirror of silicate glass of thickness 4 mm and dimensions

54.6×40.5 cm^2, hinged at the top of the cooker is used as reflector. To adjust mirror angle holes are provided on both outer sides of cooker. Two containers, each of one liter water capacity, diameter 20 cm and height 6 cm, which are appropriate for cooking requirements of two persons, are used in the present on-field studies.

The total weight of SFSC is near about 8 kg that makes it convenient in handling and cost is about 1385 INR which is reasonably low for middle income group people of developing nation.

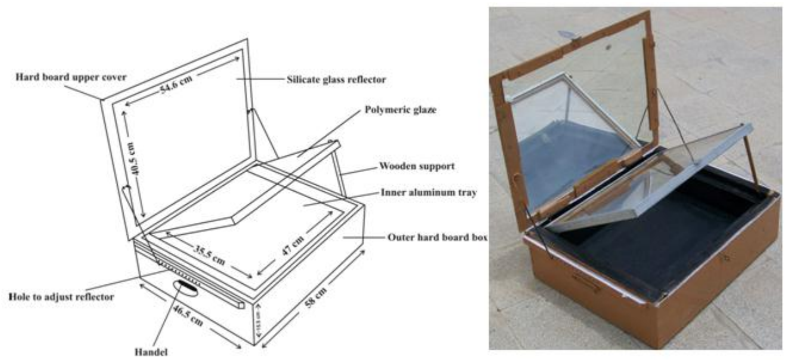

Figure 1. Schematic Diagram and Photograph of SFSC.

3. Experimental Studies

The thermal performance of a solar cooker is examined by a number of parameters suggested by many authors [11, 12, 16, 17]. In the present work we have presented the determination of two important thermal performance parameters (TPPs) that are: first figure of merit (F_1) and second figure of merit (F_2) given by Bureau of Indian standards for solar cookers. To evaluate these parameters year round on-field experiments have been conducted as per the test protocol [11, 12], that are described in this section.

3.1. Experimental Arrangements

In the years 2009-10, on-field experiments at the University of Rajasthan, Jaipur (26.92ºN, 75.87ºE) are performed and thermal performance of the SFSCs is studied on a number of days. During all experiments, the solar radiation intensity (I_s) on a horizontal surface is measured using a pyranometer (Nation Instruments Ltd. Calcutta, instrument no. 0068). CIE-305 thermometer with point contact thermocouples (accuracy 0.1 ºC) is used to measure the temperatures at different locations of the cooker; viz. the cooking fluid, the absorber plate, and the lower and upper glaze covers. Ambient temperature is measured using a mercury thermometer (accuracy 0.1ºC) and wind speed is measured by an aerometer (Prova instruments inc. AVM-03). All measurements are taken at 10 min interval, reflector is not used as per the test protocol to determine F_1 and F_2.

3.2. Thermal Performance without Water Load (Stagnation test)

In this outdoor experimental test, temperature of base plate of the cooker without water load is recorded from 10:00 to 16:00 IST and simultaneously values of insolation and ambient temperatures are also measured. No tracking of system is done due to absence of reflector.

The evaluation of the first figure of merit (F_1) is done by this test with the use of following relation [11, 12]:

$$F_1 = \frac{\eta_0}{U_{LS}} = \frac{(T_{ps} - T_{as})}{I_s} \tag{1}$$

Where η_0, U_{LS}, T_{ps}, T_{as}, I_s are the optical efficiency, overall heat loss coefficient, absorber plate temperature, ambient temperature and the insolation on the horizontal surface at the time when stagnation temperature is reached. This test has been conducted on a number of days for SFSC and measured thermal profiles are shown in Fig. 2 for different days of June.

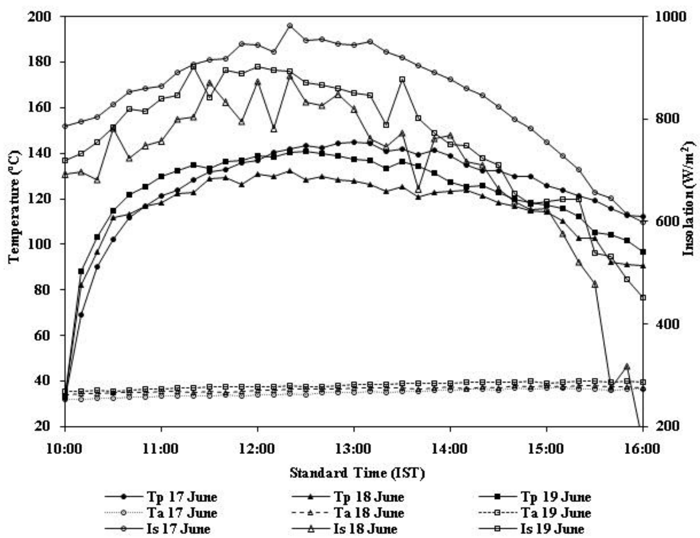

Figure 2. Variation of the bare plate temperature (T_p), ambient temperature (T_a), and the solar insolation I_s with standard time, without reflector and without load, on different days of June 2009 for SFSC.

The value of F_1 is calculated through the temperature profile of 17th June 2009. On this day the values of T_{ps}, T_{as} and insolation I_s at IST time 13:30, which is almost the centre of the stagnation state are found to be 144 °C, 35 °C and 945 W/m^2, respectively. F_1 computed through this set of data is 0.116 °Cm^2/W, even the average value of F_1 corresponding to the temperature profiles on 18th and 19th June is also around 0.116 °Cm^2/W.

3.3. Thermal performance with water load (Sensible heat test)

This experiment is performed with water load and without reflector. The evaluation of second figure of merit (F_2) of a solar cooker is done through this test procedure by using the following relation [11, 12]:

$$F_2 = \frac{F_1 (MC)_w}{A_c \tau} In \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - \overline{T}_a}{\overline{I}_s}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - \overline{T}_a}{\overline{I}_s}\right)} \right] \tag{2}$$

Where A_c is the aperture area, $(MC)_w$ is the thermal capacity of water, τ is the time during which water temperature rises from T_{W1} to T_{W2}. $\bar{I}_s$, $\overline{T_a}$ are the average solar radiation and the average ambient temperature, respectively for the time period τ.

It is recommended by BIS that this experiment should be done within ±1:30 h of the solar noon with the intensity of solar radiation above or equal to 600 W/m^2. During F_2 test, the amount of full water load for the aperture area of cooker, which is equally distributed in pots, should be calculated according to 8.0 kg water/m^2.

For SFSC the amount of water load for this test is found to approximately 1.2 kg which is evenly distributed in the two containers during the tests. With water load temperature we have also recorded temperatures of base plate, upper and lower glaze during the tests. The thermal profiles of different components of SFSC and values of insolation are shown in Fig. 3 on a sunny day of Aug. 2009. Here the instantaneous water load temperature (T_w) is the average value of instantaneous water temperatures of two containers placed in the cooker.

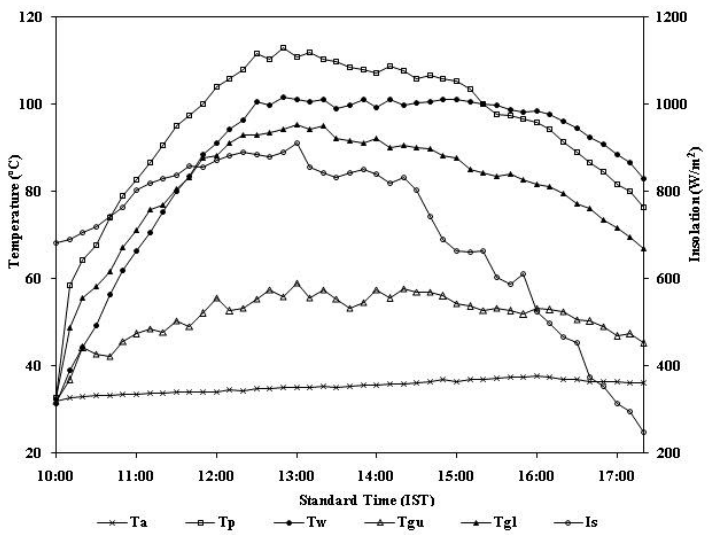

Figure 3. Temperature profiles of different components (T_a – ambient, T_p - plate, T_w - water load, T_{gu} - upper glaze and T_{gl} - lower glaze temperatures) of SFSC and variation of solar insolation, without reflector and with 1.2 kg water load on 10 Aug. 2009 with the standard time.

The temperature profile in Fig. 3 shows that initially water temperature rise is liner for the time period of 10:50 to 12:10 IST. For this time period average value of solar insolation ($\bar{I}_s$) and ambient temperature ($\overline{T_a}$) are calculated and found to be 829.8 W/m^2 and 34.6 °C, respectively. The temperatures 61.9 and 94.5 °C which correspond to time 10:50 and 12:10 IST are taken as T_{w1} and T_{w2} respectively. From these parameters value of F_2 is computed and is found to be 0.466 .

Further to examine the effect of water load change on the value of F_2, this test has been conducted with different water load amount (0.8 to 3.0 kg) distributed in two containers. The temperature profiles of some water loads (0.8, 1.0, 1.2 and 1.6 kg) are presented in Fig 4 and Fig. 5. The evaluation of second figure of merit is done in case of each water load. To determine F_2, the values of T_{w1} and T_{w2} are selected between initial liner rise of water temperature form the experimental curve as suggested by Mullick et al [18]. The values of different parameters to obtain F_2 in condition of different water loads are shown in Table 1 and values of F_2 for different water loads are plotted in Fig.6, with the experimental values of F_2 observed by different authors [18, 19] for their systems.

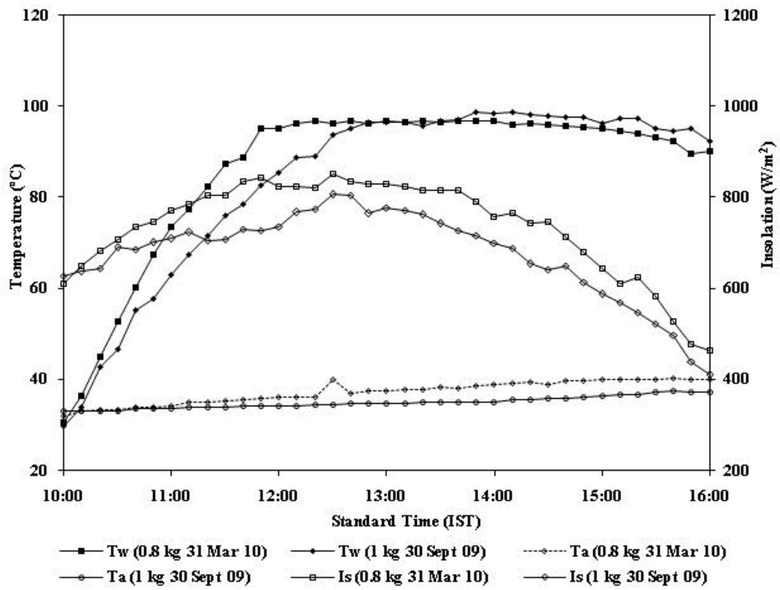

Figure 4. Variation of the solar insolation I_s , ambient temperature T_a, and temperature of different water load T_w (0.8 kg and 1.0 kg) of SFSC, without reflector with the standard time.

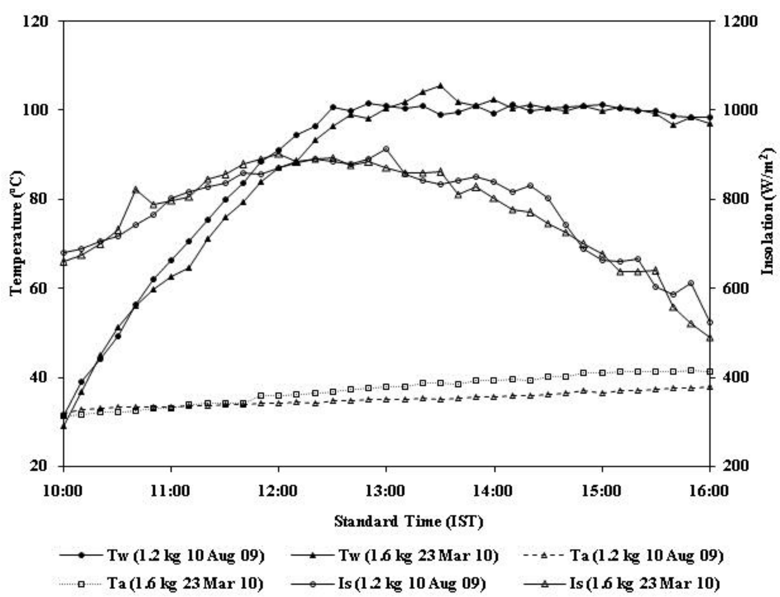

Figure 5. Variation of the solar insolation I_s , ambient temperature T_a and temperature of different water load T_w (1.2 kg and 1.6 kg) of SFSC, without reflector with the standard time.

Table 1. Values of parameters used to determine experimental values of second figure of merit (F_2) for different water loads

Parameter	Quantity of water load (in kg), equally distributed in two containers						
	0.8	**1.0**	**1.2**	**1.6**	**2.0**	**2.2**	**3.0**
Insolation $\bar{I}_s$ (W/m^2)	774.4	717.4	829.8	854.0	883.4	824.2	810
Ambient temperature $\overline{T_a}$ (ºC)	36.0	34.1	34.6	35.5	36.6	40	41
Time period τ (s)	3000	4200	4800	5400	3600	5400	6600
Value of T_{w1}(ºC)	60.3	57.8	61.9	59.7	62.5	63.3	59.9
Value of T_{w2}(ºC)	87.4	85.4	94.5	93.2	83.6	90.4	86.3
F_2	0.414	0.432	0.466	0.512	0.524	0.557	0.573

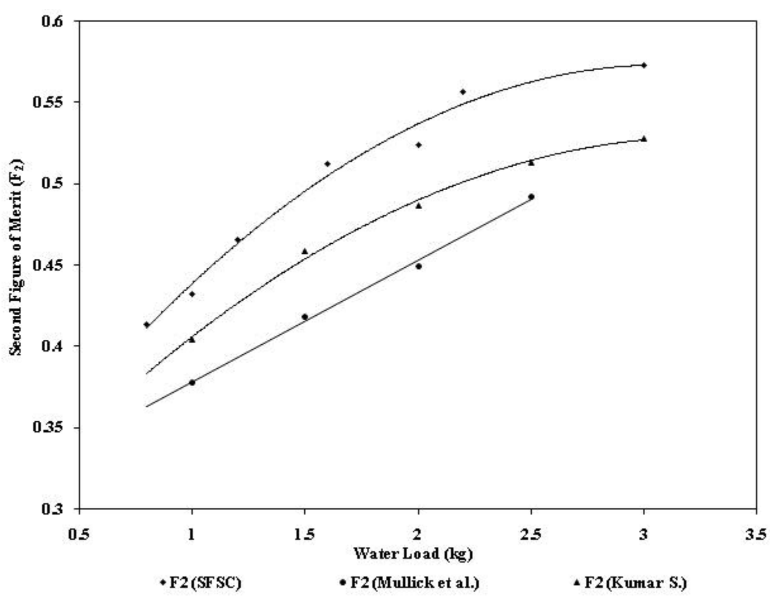

Figure 6. Variation of Second Figure of Merit (F_2) with Water Load

Fig. 6 shows that for a common load of 1.2 kg water the value of F_2 for SFSC is found to be 0.466 that is higher than the value of F_2 (0.396 and 0.426) for the systems developed by Mullick et al. [18] and Kumar [19]. For each load the value of F_2 is considerably high for SFSC than the systems of other authors [18, 19].

3.4. Thermal Performance during Cooking Test

To estimate quantitatively the rate of rise of specific food loads for satisfactory cooking for two meals we have measured the temperatures of food load during the cooking. Representative temperature profiles during two meals cooking of rice are presented here in Fig. 7, for winter season. During this cooking cooker was kept for preheating for 30 min (between 9:40 AM to 10:10 AM) for first meal cooking, whereas this period was 20 min (between 12:50 PM to 1:10 PM) for second meal cooking. Year round cooking tests have been performed in the developed cooker for different food items. The cooking times of cooking test conducted during both winter and summer months for several food items are presented in Table 2.

Table 2: Cooking Tests of Various Food Items with SFSC

Date	First meal			Second meal			Climatic condition
	Loading Time	Food items	Cooking Time	Loading Time	Food items	Cooking Time	
27-Dec. 2009	10:30	400 g rice & 800 g water	2 h 15 min	13:00	400 g rice & 800 g water	1 h 50 min	Clear sunny day
28-Dec. 2009	10:00	600 g wheat flour balls (Bati) + 150 g pulse & 450 g water	2 h 45 min	12:50	600 g green vegetable, oil & water + 200 g rice & 400 g water	2 h 30 min	Clear sunny day
31-Dec. 2009	10:10	200 g wheat daliya,200 g sugar & 800 g water	2 h 30 min	12:45	400 g potato & 250 g water + 200 g rice & 400 g water	2 h 30 min	Clear sunny day
16-Apr. 2010	10:10	300 g rice , 200 g chopped vegetable & 700 g water	2 h 10 min	_	Thick clouds	_	Partially cloudy day
17-Apr. 2010	10:10	100 g rice, 1Lt. milk & 350 g sugar (pudding) + 200 g wheat daliya & 900 g water	2 h 30 min	12:50	200 g rice, 50 g moong dal, 150 g green vegetable & 800 g water	2 h	Clear sunny day

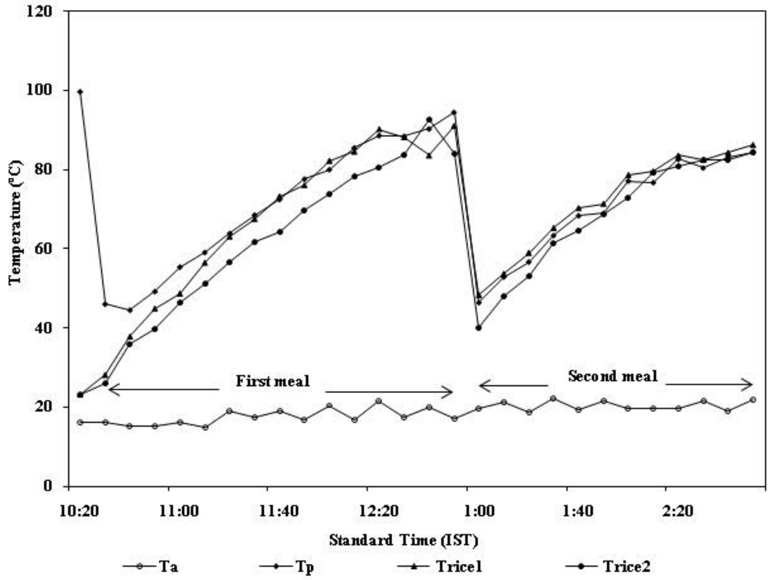

Figure 7. Temperature profile of SFSC during two meal cooking of rice on 27 December 2009 with the standard time (T_{rice1} and T_{rice2} are the temperatures of rice in the two containers and rest of the symbols are same as in Fig. 2).

Fig. 7 revels that the cooking time for first meal is about 2 h 15 min while this time is less only 1 h 50 min for second meal of cooking due to high plate temperature during loading of second meal. The cooked rice was found to be good in taste and aroma.

4. Results and Discussion

Fig. 2 illustrates that for different days of June 2009, within a very short time of 10 to 20 min bare plate temperature reaches 80 ºC and remain higher than 100 ºC for more than 5 h. On 17 June when the insolation was 945 W/m^2 and ambient temperature was 35 ºC, the stagnation temperature of bare plate was 144 ºC, which is comparable with the values reported by many authors [5-10] for their systems. Even on 18 and 19 June when insolation was significantly low (~ 800 W/m^2) and had significant fluctuation due to intermittent passage of clouds, the bare plate stagnation temperature remained around 120 ºC for more than 5 h which is reasonably long duration for satisfactory cooking. The temperature profile corresponding to 18 June is also illustrative of the fact that intermittent fluctuations have a little effect on the plate stagnation temperature. The first figure of merit (F_1) is found to be 0.116 ºCm^2/W which is as per the acceptable value suggested by Mullick et al. and BIS [11, 12] for box type solar cooker.

Fig. 3 shows that, with the full water load (1.2 kg) base plate attains 80 ºC temperatures within the 40 min and it remains higher than this temperature for more than 6 h. The water temperature reaches 80 ºC within 1:30 h and remains higher than this for more than 5 h, which is sufficient time to cook two meal of soft load. A large difference in upper and lower glaze temperature throughout the day indicates good performance of glaze material. Fig. 4 and 5 depict the thermal profiles of SFSC during different water loads. The value of second figure of merit (F_2) is measured by these experiments for different loads. The parameters which are used to measure these values are depicted in Table 1. The value of F_2 varies from

0.414 to 0.573 for the water load 0.8 kg to 3.0 kg, respectively. These values of F_2 are compared in Fig. 6 with the values of F_2 obtained by other authors [18, 19] for their systems. This figure clearly shows that value of F_2 in case of each load is higher than the values observed by others and follow the similar pattern. The curve of F_2 values observed by Mullick et al. [18] seems differ but actually this is due to availability of F_2 values only over limited load range. The value of F_2 for the recommended load by BIS that is 1.2 kg for SFSC is found to be 0.466, which is higher than the value observed by other authors [18-20] with 2 kg water load for their systems. The higher values of F_2 indicate good thermal performance of SFSC. Further Fig. 4 and 5 also illustrate that the amount of water load governs the initial rate of rise of temperature which in turn decides the cooking performance of the cooker. For water load less than 2.0 kg rate of rise of temperature is high while for water load more than 2.0 kg rate of rise is relatively low, this observation can be used for deciding the optimum load for a particular solar cooker.

In winters all the box type cookers show the poorest performance, on account of weak insolation and high incidence angles. It is quite satisfying and interesting to see that SFSC was able to cook two meals of soft load during winters also (Fig. 7); obviously it's performance, on clear days, during rest of the months remains much better than this. The cooking of various food items including boiling and baking presented in Table 2, confirm its capability to cook various Indian dishes.

5. Conclusion

Performance analysis of developed cooker is found to satisfy Bureau of Indian Standards. Calculated F_1 and F_2 values indicate that the cooker can be used for consecutive cooking on a sunny day for several food items. With small size, good thermal performance, light weight and reasonably low cost, SFSC is appropriate for cooking requirements of middle class single families of developing countries.

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Authors

Prof. Prabha Dashora is the Director of Center of Non-Conventional Energy Resource and the Head of Liquids, Polymers and Solar Energy Research Group at the Department of Physics, University of Rajasthan Jaipur, India. She has more than twenty years of teaching and research experience. Ms. Sunita Mahavar and Manisha Verma are pursuing Ph. D. from the Department of Physics, University of Rajasthan, Jaipur. Dr. Namrata Sengar has completed Ph. D. in 2009 from the Department of Physics, University of Rajasthan, Jaipur and presently teaching M.Sc. (Physics) Energy Studies at the Department of Pure and Applied Physics, University of Kota, Kota, India.