European Association for the Development of Renewable Energies, Environment and Power Quality (EA4EPQ)

International Conference on Renewable Energies and Power Quality (ICREPQ'12)
Santiago de Compostela (Spain), 28th to 30th March, 2012

Fabrication and Experimental findings of a Solar Rice Cooker

S. Mahavar, M. Verma, P. Rajawat and P. Dashora

[1] Department of Physics
University of Rajasthan
Jaipur , 302015 Rajasthan (India)
Phone 00917737424397, e-mail: **smjpr1986@gmail.com**, **pdashora@yahoo.com**

Abstract. This paper presents fabrication details and experimental findings of a Solar Cooker that is designed to cook 400 g rice per meal; it is named as Solar Rice Cooker. The main features of SRC are (i) it is fabricated mainly by transparent acrylic sheets (ii) it is light in weight (iii) its size is small yet its thermal performance is comparable to the solar cookers developed so far (iv) the rice cooking is convenient in this and (v) the cooked food has good taste and aroma. A theoretical formalism has been developed by authors to compute the contribution of the transparent vertical side walls to enhance absorbed beam radiation flux by the container. A significant enhancement has been observed in available radiation due to the novel design (transparent trap) of the cooker. Various reasons for the selection of trap material have also been discussed in this paper. The thermal profiles of SRC are measured under different conditions; the maximum temperature of the upper surface of the container during cooking is found to be 142 °C. The water temperature inside the container is also recorded for two meal cooking. The thermal performance of SRC is also compared with the solar cookers developed by other authors.

Key words

Solar cooker, rice cooker, polymeric glaze

1. Introduction

Rice is the second largest produced cereal in the world; its consumption is about 85.9 kg/year, per capita (milled rice). It is a part of meal in most of the Asian countries. A large portion of household energy is attributed to rice cooking [1]-[3]. In the current scenario of conventional cooking fuel energy crisis, designing of rice cooker which utilizes solar energy for rice cooking, can significantly reduce the cooking energy consumption world over. It can also help to reduce several inherent risks to environment, economy and public health, that arise due to consumption of the available cooking fuels (wood, dung, kerosene, LPG, coal etc).

With this stimulus we have fabricated a Solar Rice Cooker (SRC). This Solar Rice Cooker has good thermal and cooking performance. Due to its small size (outer dimension: 41 × 41×16 cm^3) and light weight (only 5.5 kg), it is very convenient in handling among a number of solar cookers developed and studied by many authors [4]-[6]. SRC is suitable to cook 400 g rice in 2 to 2.5 h twice in a day depending on the availability of solar insolation (~700 to 900 W/m^2). The cost of SRC is only 2500 INR that makes it economically affordable rice cooker for the middle income group people of developing nations.

2. Fabrication of Solar Rice Cooker (SRC)

During last one decade authors have made a number of solar cookers keeping specific categories of users in mind [7]-[9]. The solar cooker studied in this paper is specially designed for rice cooking.

A. Modelling

The basic components of a conventional box type solar cooker are (i) absorber plate (ii) transparent cover (glaze) (iii) insulation material and (iv) cooking containers. The black painted metal absorber tray with transparent cover makes a trap for solar radiation. The cooking containers which are put inside the trap use available solar energy inside the trap for cooking. To minimize the heat losses from the surrounding atmosphere this heat trap is insulated from sides and at the bottom surface.

The energy balance in the system for a non steady or transient state can be written as [10], [11].

$$q_u = A_p S - q_l \tag{1}$$

where q_u is the useful heat gain, S is the incident solar flux absorbed in the absorber plate, A_p is the area of the absorber plate, q_l is the rate at which heat is lost by convection and re-radiation from the top and by conduction and convection from the bottom and sides. The flux incident on the top cover of the collector is given by

$$I_T = I_b r_b + I_d r_d + (I_b + I_d) r_r \tag{2}$$

where I_b is the beam radiation, I_d is the diffuse radiation, r_b, r_d are the tilt factors for beam and diffuse radiation respectively, and r_r is the radiation shape factor for a tilted surface with respect to the sky [10], [12].

The flux S absorbed in the absorber plate can be written as

$$S = S_b + S_d \tag{3}$$

$$S_b = I_b r_b\, (\tau\alpha)_b \;;\; S_d = \{I_d r_d + (I_b + I_d) r_r\}\, (\tau\alpha)_d \tag{4}$$

where τ is the transmissivity of the glaze material, α is the absorptivity of the absorber plate, $(\tau\alpha)_b$ and $(\tau\alpha)_d$ are the transmissivity-absorptivity product for beam and diffuse radiation falling on the collector, respectively.

In case of small solar cookers due to opaque insulated walls a considerable area of the containers remains in shadow [9]. These shadows not only reduce the total available radiation in the trap but also lead to large thermal stress on the glaze and, non-uniform heating and cooking of food load. On the basis of these observations authors have made a novel design solar cooker for rice cooking. For easy handling the size of the solar rice cooker (SRC) is kept small ($41 \times 41 \times 16$ cm^3) and to compensate reduction in aperture area (A_a) due to reduction in size, the side vertical walls have been made of transparent double glaze. In SRC instead of a square absorber tray a large size cylindrical container has been used. So the solar radiation which passes through upper and side glazes may be directly absorbed by the cooking container. For SRC the cooking container itself works as an absorber plate.
The expression for the contribution of beam radiation entering through the upper and side glazes of the box in the flux absorbed by the container can be deduced by the well known relations of geometrical optics [10]. A brief description is given below:

The overall transmissivity 'τ' of a transparent cover is given by:

$$\tau = \tau_r \tau_a \tag{5}$$

where τ_r is the transmissivity obtained by considering only reflection and refraction, τ_a is the transmissivity obtained by considering absorption.

$$\tau_r = \frac{1}{2}(\tau_{rI} + \tau_{rII}) \tag{6}$$

$$\tau_{rI} = \frac{1 - \rho_I}{1 + (2M - 1)\rho_I} \tag{7}$$

$$\tau_{rII} = \frac{1 - \rho_{II}}{1 + (2M - 1)\rho_{II}} \tag{8}$$

where τ_{rI} and τ_{rII} are transmissvities of the two components of polarization, M is the number of covers and ρ_I and ρ_{II} are the reflectivities of the two components of polarization, which may be expressed as:

$$\rho_I = \frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)} \tag{9}$$

and

$$\rho_{II} = \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)} \tag{10}$$

where θ_1 and θ_2 are the angle of incidence and refraction, respectively, at the glaze surface. The direction of the incident and refracted beams are related to each other by Snell's law i.e.

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} \tag{11}$$

where n_1, n_2 are refractive indices of the two media.

$$\tau_a = e^{-K\delta_c/\cos\theta_2} \tag{12}$$

where extinction coefficient K is a property of the cover material, δ_c is the thickness of the cover material and θ_2 is the angle of refraction.

If θ is the angle between an incident beam I_{bn} and the normal to a plane surface, then the equivalent flux falling normal to the surface is given by $I_{bn} \cos\theta$. The angle of incidence θ for any surface is given by:

$$\begin{aligned}\cos\theta = {} & \sin\phi\,(\sin\delta\cos\beta + \cos\delta\cos\gamma\cos\omega\sin\beta) \\ & + \cos\phi\,(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta) \\ & + \cos\delta\sin\gamma\sin\omega\sin\beta\end{aligned} \tag{13}$$

where ϕ, δ, β, γ, ω are the latitude of the location, the declination angle, the tilt angle of the surface, the surface azimuth angle and the hour angle, respectively. It is seen that very often measuring instruments give the values of solar radiation falling on a horizontal surface that is:

$$I_b = I_{bn} \cos\theta_z \tag{14}$$

where θ_z is the zenith angle.

Hence the absorbed flux by cooking container due to only beam radiation may be written as:

$$S_b = I_b r_b\, (\tau\alpha)_b \tag{15}$$

where $$r_b = \cos\theta / \cos\theta_z \tag{16}$$

In the proposed type of heat trap, radiations enter the trap through the upper horizontal surface as well as vertical side walls. For such case the rate of energy absorbed by container due to only beam radiation $(AS)_b$ can be written as:

$$(AS)_b = A_{us}S_{us} + A_{sw}S_{sw} + A_{ew}S_{ew} + A_{nw}S_{nw} + A_{ww}S_{ww} \quad (17)$$

where A's are areas of the container intercepting the radiation and S's are corresponding flux absorbed. The subscripts us, sw , ew , nw, ww are used for upper surface and, south, east, north and west walls, respectively.

Using Eq. 5 to 16 and assuming all five glazes are constructed by polymeric double sheets having the properties shown in Table 1, values of S_b for different glazes of SRC are computed on an equinox day (21 March) with Indian standard time (IST) variation for Jaipur (26.92ºN, 75.87ºE), India. For this computation insolation data (I_s = global, I_b = beam radiation falling on a horizontal surface), at Jaipur on equinox day in March 2006 has been procured from Indian metrological department (IMD), Pune. The results are plotted in Fig. (1)

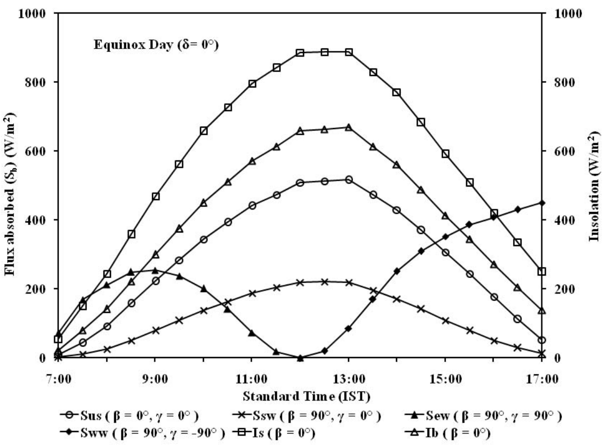

Fig. 1: Variation of the absorbed beam radiation flux (S_b) for different glazes (subscript us, sw , ew , ww are used for upper surface and, south, east and west walls, respectively) and values of global (I_s) and beam radiation (I_b) on horizontal surface at equinox day (δ = 0˚), with standard time (IST).

Fig. 1 reveals that only walls due south, east and west contribute to increases S_b on an equinox day (δ = 0°). The contribution of north wall can be seen on summer solstice (δ = 23°). The values of S_{ss} show that south wall significantly increases S_b values over the whole day. The east and west walls contribute during forenoon and afternoon, respectively. Although the area of each transparent side wall (34 × 9 cm^2) is much less than the upper surface area (34 × 34 cm^2) yet their contributions in the rate of energy absorbed by the container remain significant over the day. For beam radiations these can be easily calculated by Eq. 17. This contribution is expected to increase further if diffused radiations are also considered in calculation.

B. Selection of Material

Usually to minimize heat losses due to transparent cover system by re-radiation and convection a double layer of glass with air gap 1.3 to 2 cm is used as a glaze material in solar cookers. Fragility and weight are the two major drawbacks of glass glazes, to remove both these limitations authors decided to explore another suitable material for glaze. On the basis of careful survey of available data of thermal, optical and mechanical properties of hard transparent polymers; poly (methyl methacrylate) (PMMA)) and polycarbonate (PC) have been found suitable for glaze materials [6]. Properties of these materials are listed in Table 1, which clearly show that on account of low values of extinction coefficient, refractive index and density both PMMA and PC are better than glass, but the cost and weight of PC glaze are relatively higher than those of PMMA glaze, therefore PMMA is found to be the most promising substitute of glass to fabricate all transparent glazes of SRC.

The variation in the transmissivity (τ) for double glaze of these materials, for beam radiations, over the whole day length, due to variation in the angle of incidence (θ), on horizontal surface at Jaipur (26.92ºN, 75.87ºE) India, for equinox day (δ = 0˚) have been calculated using Eq. 5 to 13 and Table 1. The calculated values are plotted in Fig. 2.

Table 1: Properties of different glaze materials

Properties	**Glaze material**		
	Glass	**PMMA**	**PC**
Refractive index	1.52	1.49	1.58
Extinction coefficient (m^{-1})	15	0.05	0.05
Density (kg/m^3)	2450	1172	1177
Thickness of single sheet (mm)	3.94	2.75	2.9
Cost (Rs./m^2)	485	915	1830

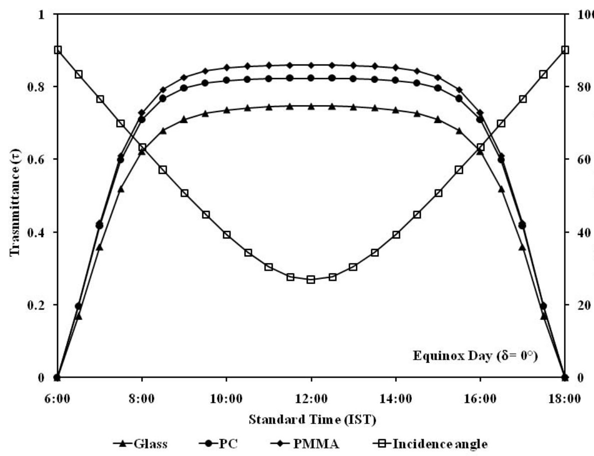

Fig. 2: Variation of transmittance for beam radiation for different glaze materials and value of incidence angle at equinox day (δ = 0˚), with standard time (IST).

This figure reveals that transmittance of PMMA and PC double glaze are 10 to 12% and 7 to 9% higher than that of glass, respectively between effective time duration of 8:00 to 16:00 IST.

C. Structural Details of SRC

The outer dimensions of SRC are 41 × 41 × 16 cm^3 and the inner dimensions are 34 × 34 × 9 cm^3. The upper surface and all vertical side walls have been constructed of double sheets of transparent acrylic (PMMA) of thickness 2.75 mm with air gap of 13 mm. The bottom surface has been insulated by the use of ceramic fiber of thickness 2.5 cm. At this insulated surface a polymeric mirror has been fixed at which a cylindrical aluminum container is kept with a wooden stand of height 1 cm. The wooden stand prevents direct touch of bottom reflector and cooking container. The container's diameter and height are 32 cm and 6.5 cm, respectively. The container is painted by black matt paint. Another polymeric reflector (34.5 × 34.5 cm^2) is also attached with cover lid of SRC. This reflector can be adjusted at different angles to get reflected solar radiations on cooking container. For convenience in handling a water proof hand bag is also designed to keep SRC when it is not used for cooking.
The schematic diagram and a photograph of SRC are shown in Fig. 3.

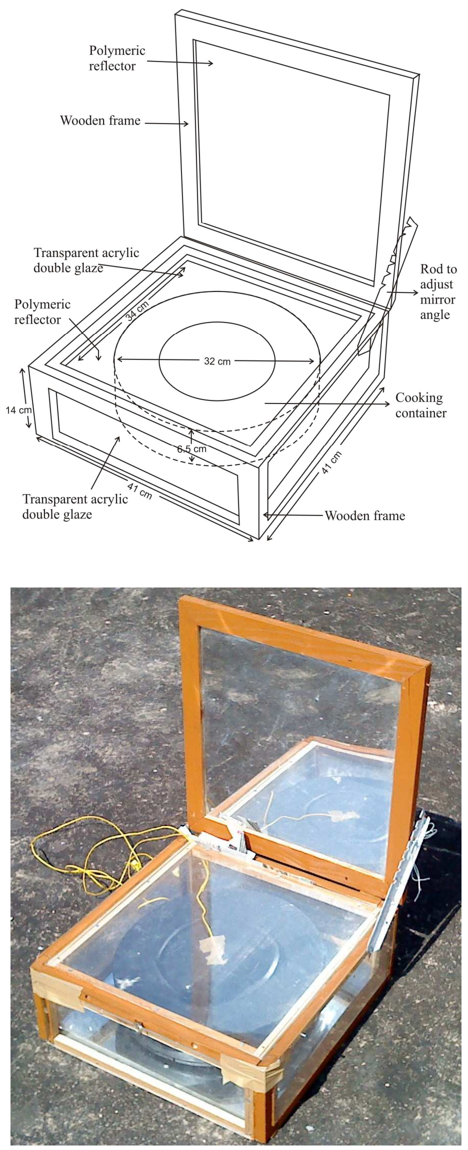

Fig. 3: Schematic diagram and photograph of SRC

3. Experimental Studies

On a number of days the experimental studies of SRC have been conducted and the representative results are presented in this section.

A. Experimental Arrangement

During all experiments, the solar radiation intensity (I_s) on a horizontal surface has been measured using a pyranometer (Nation Instruments Ltd. Calcutta, instrument no. 0068). CIE-305 thermometer with point contact thermocouples has been used to measure the temperatures at different locations of container. The ambient temperature is measured using a mercury thermometer placed in an ambient chamber. To measure water temperature inside the container, a small hole with air tight cork, is provided at the upper surface of container.

B. Thermal Performance

The cooking of 400 g rice which needs 800 g water for cooking (total load 1.2 kg) in a solar cooker, is possible if it is kept at 80 ºC, for at least 40 min. Therefore, the thermal performance of SRC is measured with 1.2 kg water load in a container for two situations: (i) when water is loaded for full day length (ii) when water is loaded for pre noon to mid noon and then the same amount of water is reloaded at room temperature as the representative of the second meal cooking for the duration of noon to afternoon. During both the experiments temperatures of upper and lower surfaces of the container and inside water temperature with solar insolation values are measured with Indian standard time (IST). These temperature profiles are shown in Fig. 4 and 5.

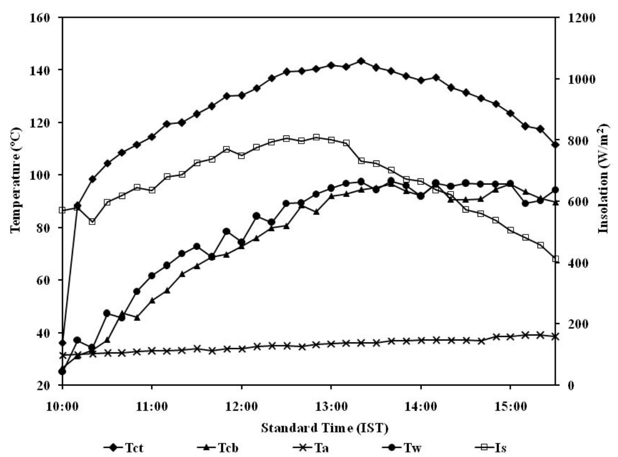

Fig. 4: Temperature profiles of different region of SRC and variation in solar insolation (I_s) (with reflector, with 1.2 kg water load for full day length on 26 Sept. 2011) with the standard time (T_{ct}, T_{cb} are container's top and bottom surface temperatures respectively. T_a,T_w are ambient and water temperatures, respectively.)

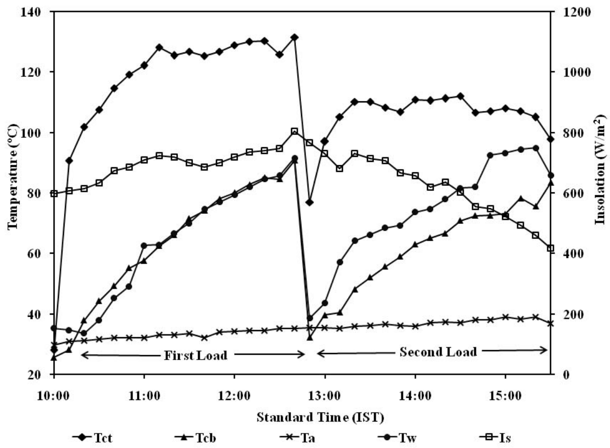

Fig. 5: Temperature profiles of different region of SRC and variation in solar insolation (with reflector , with 1.2 kg water reloded at 13:00 IST on 11 Oct. 2011) with the standard time (all the symbols are same as in Fig. 4).

C. Cooking Performance

Cooking of 400 g rice, twice in a day is also performed for many days. During the cooking, temperatures of different regions of container are also measured; one of the representative data is presented in Fig. 6.

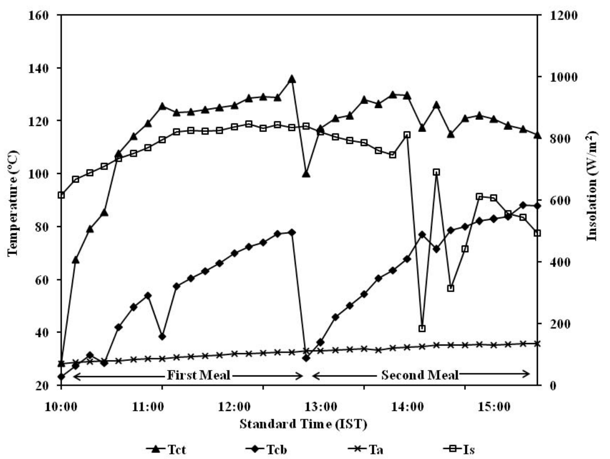

Fig. 6: Temperature profiles of different region of SRC during two meal cooking (400 g rice /meal) and variation in solar insolation (with reflector on 25 Sept. 2011) with the standard time (all the symbols are same as in Fig. 4).

D. Comparative Study

In the experimental study of a box type solar cooker the maximum temperature attained by the absorber plate without any water load, is an important figure and many authors have mentioned it for their developed solar cookers. In the case of SRC if upper surface of container is assumed like absorber plate, then maximum temperature attained by it can be compared with absorber plate. This comparison is presented in Table 2.

Table 2: Comparison of performance of SRC with other box type solar cookers

Ref.	**Max. Temp. (ºC)**	**T_a (ºC)**	**Time (IST)**	**I_s (W/m^2)**	**Date of exp.**
Nahar [4]	132	28	14:00	760	-
Negi [5]	140	27	12:00	750	Mar. 2002
Harmani [6]	140	48	12:00	960	23/7/ 2008
SRC	142	36	13:00	800	26/10/ 2011

4. Experimental Findings

Fig. 4 shows that the upper surface of cooking container attains 100 ºC temperatures within only 20 min and the highest temperature attained by this is about 142 ºC that is comparable with the other box type solar cookers as revealed from Table 2. It is found that water temperature inside the container remains higher than 80 ºC for long duration i.e. 5 h this indicates low value of heat loss coefficients for transparent side walls.

The temperature profiles in case of reloading of 1.2 kg water (Fig. 5) shows that during first loading water temperature remains at 80 ºC for more than 30 min before 13:00 IST and after that in second loading it attains this temperature within 1.5 h i.e. the cooking of 400 g rice that need 800 g water to be cooked can be easily done twice in a day. Fig. 6 shows the thermal profile during actual cooking of 400 g rice. The cooking of first meal is done from 10:00 to 13:00 IST and second meal is cooked from 13:00 to 15:30 IST. It is found that the rice cooked in SRC has better taste and aroma than the rice cooked through conventional methods besides being rich in nutrients on accounts of slow cooking. In addition with the specific containers, SRC can also be used to cook some special Indian dishes viz. Idly and Khaman.

5. Conclusion

The developed solar cooker has the novel feature of transparent side walls that enhance solar radiation inside the trap and improve the thermal and cooking performance. Due to less dense transparent glaze material SRC is light in weight. Its thermal performance is found satisfactory to cook two meals (rice) on a clear day. Due to reasonable cost, this rice cooker is within the reach of middle income group people of developing countries.

Acknowledgement

Authors, Sunita Mahavar, Manisha Verma and Poonam Rajawat are grateful to Council of Scientific and Industrial Research (CSIR), New Delhi, for grant of Junior Research Fellowship (JRF) for pursuing their Ph.D. work.

Reference

[1] UNCTAD Secretariat from the Food and Agriculture Organization of the United Nations (FAO) data, (http://www.unctad.org/infocomm/anglais/rice/market.htm)

[2] P.S. Anoopa, S. Dayana, N.S. Nithya and M. Prajitha, " Energy consumption benchmark studies on parboiled rice cooking in Kerala", Energy Management Centre-Kerala, India.

[3] P. Roy, D. Nei, T. Orikasa, H. Okadome, M. Thammawong, N. Nakamura and T. Shiina, "Cooking properties of different forms of rice cooked with an automatic induction heating system rice cooker", Asian Journal of Food and Agro-Industry, 2010, Vol. 3 (04), pp. 373-388.

[4] N.M. Nahar, "Performance and testing of an improved hot box solar cooker", Energy Conversion and Management 1990, Vol. 30, pp. 9-16.

[5] B.S. Negi and I. Purohit, "Experimental investigation of a box type solar cooker employing a non-tracking concentrator", Energy Conversion and Management, 2005, Vol. 46, pp. 577-604.

[6] A. Harmim, M. Belhamel, M. Boukar and M. Amar, "Experimental investigation of a box type solar cooker with a finned absorber plate", Energy, 2010, Vol. 35, pp. 3799-3802.

[7] S. Mahavar, N. Sengar, M. Verma and P. Dashora, "Extensive experimental studies of a Single Family Solar Cooker", International Journal of Energy, Information and Communications, 2011, Vol. 2(4), pp. 169-179.

[8] N Sengar, P. Dashora, M. Gupta and S. Mahavar "Experimental studies, energy saving and pay back period of a cylindrical Building Material Housing solar cooker", International Journal of Energy, Information and Communications, 2011, Vol. 2(3), pp. 75-84.

[9] S. Mahavar, N. Sengar, M. Verma, P. Rajawat and P Dashora, "Design development and performance studies of a novel Single Family Solar Cooker", Renewable Energy, 2011, accepted for publication.

[10] S.P. Sukhatme, Solar energy- Principle of thermal collection and storage, second ed., Tata McGraw-Hill Publishing Company Limited, New Delhi, 2007.

[11] K. Schwarzer and M.E.V. Silva, "Characterisation and design methods of solar cookers", Solar Energy, Vol. 82 (2008), pp. 157-163.

[12] D. Y. Goswami, F. Kreith and J. F. Kreider, Principle of solar engineering, second ed., Taylor & Francis, USA, 2000.