Experimental Studies, Energy Savings and Payback Periods of a Cylindrical Building-Material-Housing Solar Cooker

Namrata Sengar[1], Prabha Dashora[2], Manjari Gupta[2] & Sunita Mahavar[2]
[1]*Dept. of Pure & Applied Physics, University of Kota, Kota, India.*
[2]*Dept. of Physics, University of Rajasthan, Jaipur, India.*
E-mail: namratasengar@rediffmail.com, pdashora@yahoo.com

Abstract

This paper presents the design, experimental studies, energy savings and payback periods of a building-material-housing solar cooker (BMHSC), which can be used as a domestic or an animal feed cooker. Experimental studies related to the temperature profiles, cooking tests and estimation of figures of merit have been reported. A comparative thermal performance study of the BMHSC with a commercially available solar cooker (CSC) reveals that the performance of the BMHSC is slightly better than the CSC. The average values of the figures of merit (F_1, F_2) for the BMHSC and the CSC are 0.12, 0.47 and 0.12, 0.43, respectively. The payback periods of the BMHSC are in the range of four months to around three years for various fuels.

Keywords*: Building-material-housing solar cooker, figures of merit, energy savings, payback periods.*

1. Introduction

With the increase in population, industrialisation, economic growth, technological advances and changes in the life style, the consumption of energy in the developing countries is increasing at a fast pace. In spite of the maximum harnessing of the available fossil fuels and their imports from the other countries, the supply of power in a cost effective manner to the residents is becoming a highly challenging task for the governments of almost all the developing nations. Fossil fuel reserves are limited, mainly concentrated between few countries of the world and are depleting very fast. An analysis of the energy consumption pattern reveals that in the developing nations the major share of energy used is for cooking and water heating purposes. Further, for cooking and water heating, both the rural and the urban low-income households of the developing countries depend on expensive and inefficient fuels like wood, dung, kerosene, coal etc. [1-3]. On the one hand use of bio-fuels with conventional low efficiency (~10%) chulhas/stoves in poorly ventilated kitchens results in the economic burden on the poor households, on the other hand it leads to various smoke related diseases and fire accidents [4-7].

Therefore, in the current energy scenario, maximum utilization of the available renewable energy resources has become almost mandatory for every country of the world [8]. India is one of the largest solar radiation receiving countries, still solar energy applications have not gained widespread acceptability. Keeping in mind the above-mentioned aspects authors are working on the design, development and study of solar thermal appliances, in particular on solar cooker and water heater. During last decade, authors have developed a wide variety of user need based solar cookers ranging from light weight cardboard makes to fixed structure building material ones [9-13].

This paper presents the design, experimental studies and economic analysis of a cylindrical building-material-housing solar cooker (BMHSC), which can be used as a domestic or an animal feed cooker. The solar cooker has been designed to reduce the problem of transportation and would be affordable for lower and middle-income group households. A comparative thermal performance study of the developed solar cooker with a commercially available fibre body solar cooker (CSC) has been reported. The values of the payback periods for the developed cooker and commercially available cooker with respect to the various fuels such as fuel wood, charcoal, kerosene, LPG and electricity have also been presented.

2. Design Details

2.1 Building-material-housing Solar Cooker (BMHSC)

The building-material-housing solar cooker (BMHSC) is a hotbox type solar cooker, which has been installed at an open place on the rooftop. The housing of this cooker has been built up of local masonry bricks and cement plaster (Fig. 1). This structure is cylindrical in shape with the top inclined at 10° with the horizontal and facing south. The shape and inclination have been adopted such that the shadowing of the base plate is reduced. A cylindrical blackened metal tray made of used oilcans, of diameter 0.56 m. and depth 0.076 m has been used as absorber. Around 3.5 cm. of insulation of thermal conductivity 0.035 W/mK is filled at the bottom and sides of the cooker. The glaze has been fabricated through two 3 mm thick transparent polymeric sheets with 13 mm air gap in between. A lightweight polymeric adjustable reflector is used with it (Fig. 2). The mark 'A' shows the morning position of the reflector, whereas 'B' and 'C' represent the noon and afternoon positions, respectively. The absorber area of the structure is 0.25 sq.m.

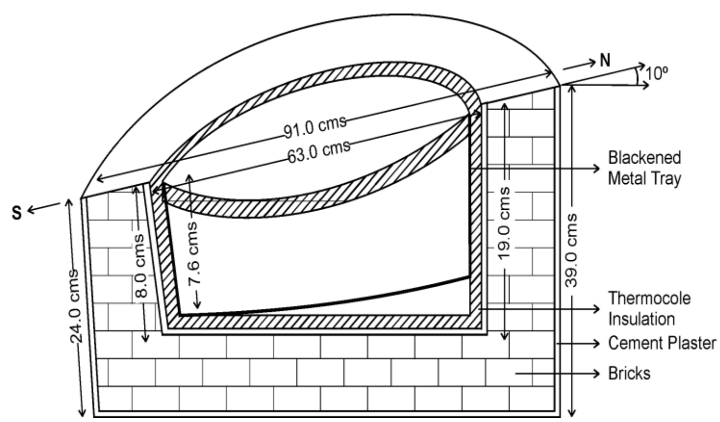

Figure1. Sectional view of Building-Material-Housing Solar Cooker (BMHSC).

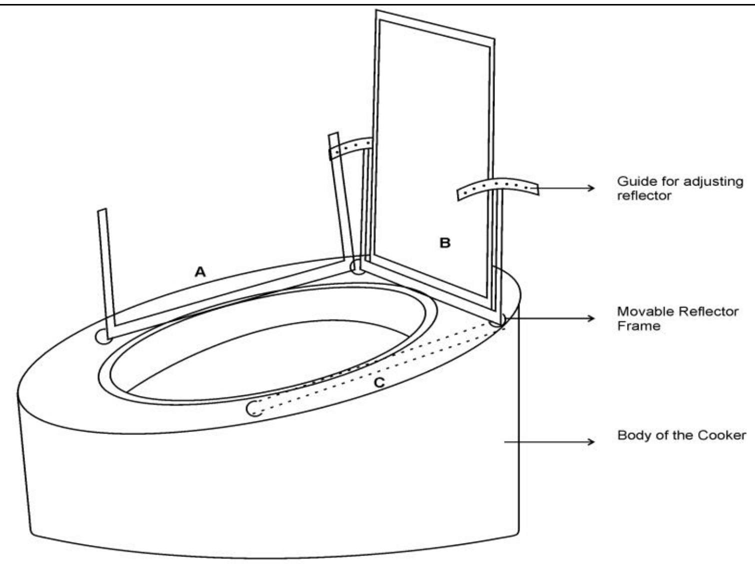

Figure 2. Building-Material-Housing Solar Cooker with Light Weight Adjustable Reflector.

2.2 Commercial Hotbox Solar Cooker (CSC)

The commercial solar cooker that has been used for comparison is a fibre body hotbox solar cooker. The bottom of the tray has dimensions 40 cm × 40 cm. The upper dimensions of tray are 46 cm × 46 cm. The walls of the tray are inclined outwards at 20.2° with the vertical. The depth of the tray is 8.4 cm. The thickness of insulation at the bottom is 5 cm and along the sides it is 3 cm. The solar cooker consists of glass glaze (50 cm × 50 cm.) and glass mirror (46 cm × 46 cm.). The glass glaze is made up of two glass sheets 4 mm thick with 1.5 cm of air in between. The glaze is placed horizontally over the absorber tray (Fig. 3).

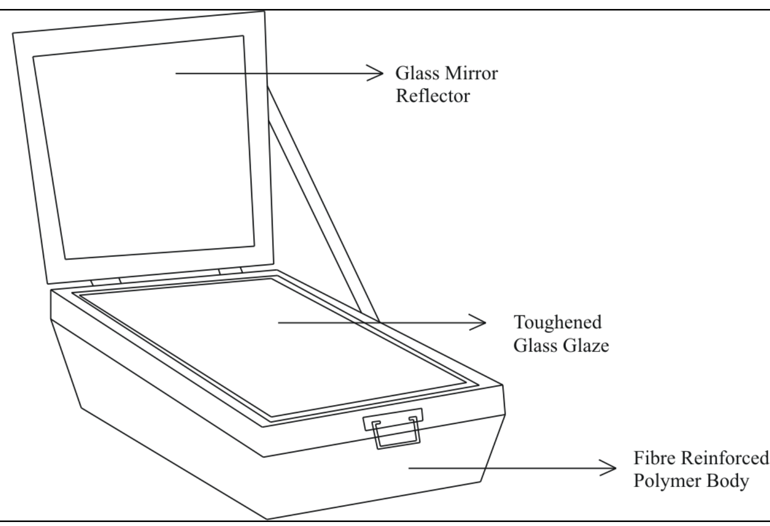

Figure 3. Commercial Hotbox Solar Cooker (CSC)

3. Experimental Studies

3.1 Thermal Performance

For studying the thermal performance of the cookers experimentally, the temperature profiles of the water and base plate have been recorded. During the experiment cookers are loaded with water in four identical containers, each of diameter 16.5 cm.

Though observations have been taken for various days over a long period, here some of the representative observations are presented. The temperature profiles for water and base plate of the BMHSC without reflector have been shown in Fig. 4 for different months. The corresponding ambient temperatures have also been shown in the same figure. During the experiment the BMHSC has been loaded with 2 kg. of water in four containers. Fig. 5 presents the temperature profiles of the base plate and water temperatures for the BMHSC and CSC when each is loaded with 2kg. of water in four containers and both the cookers are

without reflector. Fig. 6 shows the temperature profiles of the base plate and water temperatures for the BMHSC and CSC when each is loaded with 2 kg. of water in four containers and both the cookers are with reflector.

Table 1 shows the mean values and t-test results for one-tailed directional test of two independent variables. Here the two independent variables are the water temperatures in the cookers BMHSC and CSC without reflector at different time. The sample number is sixteen. The cookers have been loaded with water at 11:00 a.m. so the mean values are same at this instant but afterwards there is difference in the temperatures of water which is reflected in the values at 12:00, 13:00 and 14:00 standard time (Indian).

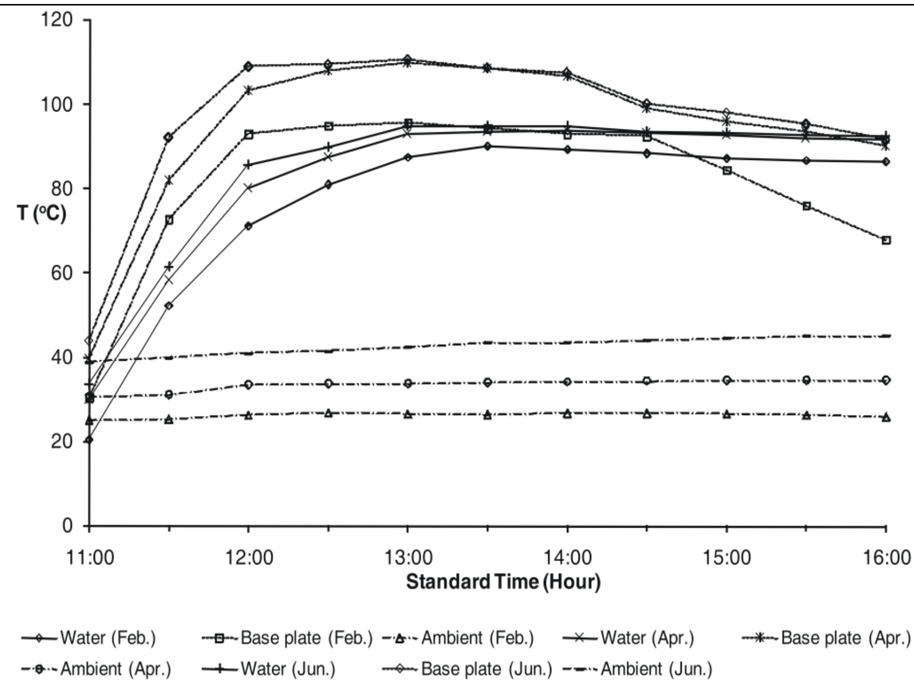

Figure 4. Temperature profiles for water and base plate of the BMHSC without reflector along with ambient temperatures (T) with Indian standard time for different months (Feb., Apr. and Jun.).

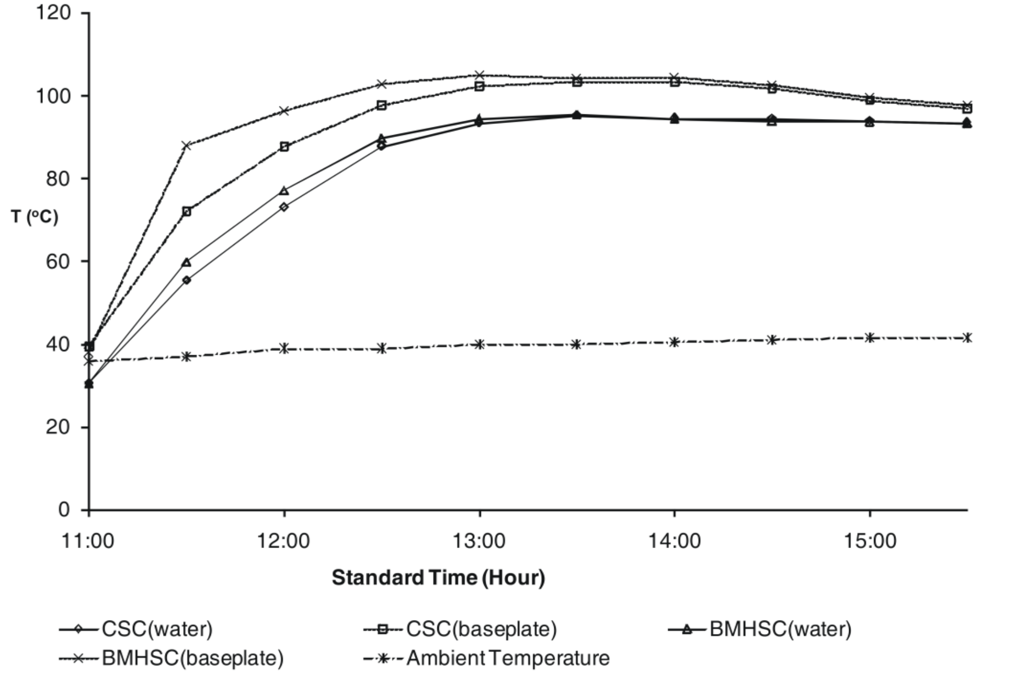

Figure 5. Temperature profiles of the water and base plate of the CSC and BMHSC with standard time when cookers are without reflector and each is loaded with 2 kg. of water.

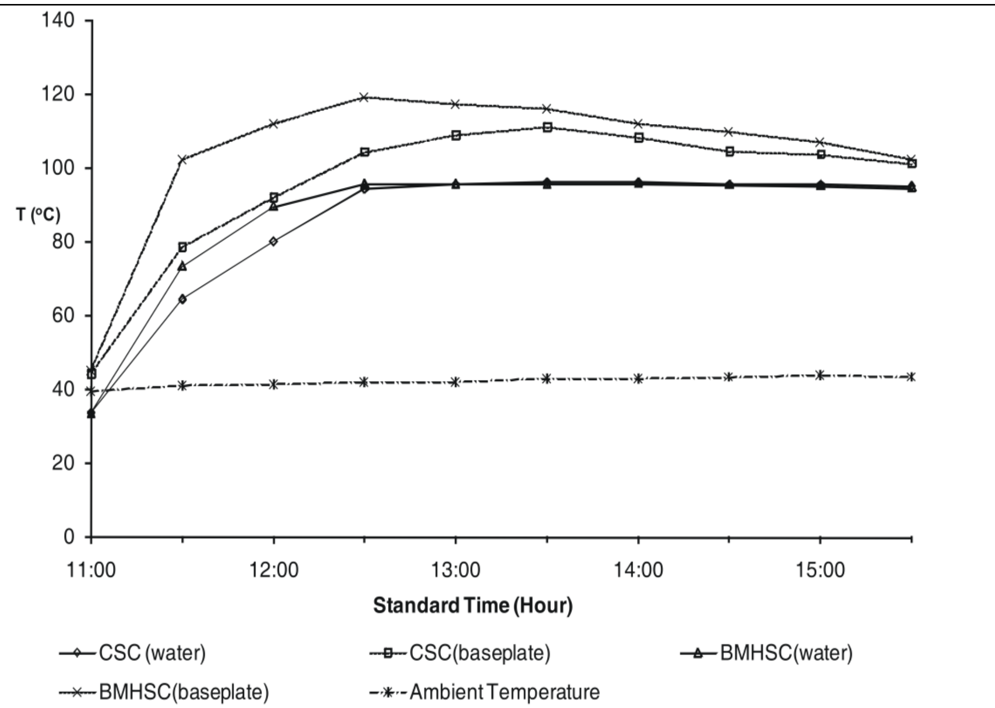

Figure 6. Temperature profiles of the water and base plate of the CSC and BMHSC with Indian standard time when cookers are with reflector and each is loaded with 2 kg. of water.

Table1. The mean values and t-test values for water temperatures in the cookers BMHSC and CSC (sample number is 16 and df=14).

Loading Time (Indian Standard Time)	BMHSC -Mean	CSC -Mean	t-test
11:00	27.9	27.9	-
12:00	77.5	69.8	2.31
13:00	93.9	90.8	2.24
14:00	95.7	93.9	3.51

Level of Significance for a Directional t-Test					
df	0.05	0.025	0.01	0.005	0.0005
14	1.76	2.14	2.62	2.98	4.14

3.2 Cooking Performance

Along with the thermal performance study, extensive domestic and animal feed cooking has also been carried out. The cooking performance of the BMHSC has been observed on various days for boiling and baking applications. Cooking of rice, pulses, beans, vegetables etc. has been done; some of the representative observations have been reported in Table 2. Four kg. of soaked animal food has been cooked in the cooker without and with reflector; and it has been found that four kg. of animal feed can be easily prepared in this cooker.

Table 2. Cooking Tests for the BMHSC with Reflector Tracked at an Interval of One Hour.

Month	Loading Time	Food	Cooking Time (Method)
APR	10:00 a.m.	1 kg. rice + 1.5 kg. water	2 hr (Boiling)
APR	10:00 a.m.	0.8 kg. lentil + 1.6 kg. water	2 hr (Boiling)
JUL	9:30 a.m.	1 kg. kidney beans + 0.8 kg. water	3hr 20 min. (Boiling)
AUG	10:00 a.m.	2.2 kg. semolina	2 hr 15 min. (Roasting)
AUG	10:30 a.m.	1.5 kg. peanuts	2 hr 15 min. (Roasting)
SEP	10:00 a.m.	1.8 kg of wheat flour balls (bati-local recipe)	2hr 45 min. (Baking)

3.3 Figures of Merit

For the evaluation of the thermal performance of solar cookers and to compare and quantify the performance of different solar cookers, test procedures have been described by the Bureau of Indian Standards [14-15] which have been further revised [16]. The first figure of merit is obtained through a stagnation test without load. The second test involves the sensible heating of full load of water (8 kg/sq.m.) in the containers and through this test the second figure of merit is obtained.

The first figure of merit (*F1*) for thermal performance of solar cookers is the ratio of the optical efficiency to the heat loss factor. It is mathematically defined as

$$F_1 = \frac{T_{ps} - T_{as}}{H_s} \quad (1)$$

where T_{ps} is the plate stagnation temperature (°C), T_{as} is the ambient temperature at stagnation (°C) and H_s is the solar insolation at stagnation (W/m^2).

The second figure of merit (*F2*) takes into account the heat exchange efficiency of cookers and is obtained through the sensible heating test of specified load of water. The second figure of merit is evaluated through the following relation

$$F_2 = \frac{F_1 (MC)_w}{A\tau_m} ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - T_a}{H}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - T_a}{H}\right)} \right] \quad (2)$$

where F_1 is the first figure of merit, $(MC)_w$ is the heat capacity of water in the containers, τ is the measured time for sensible heating of water between two known temperatures T_{w1} and T_{w2} of water, T_a is the average ambient temperature over the time period τ_m, H is the average insolation over the horizontal surface for the time period τ_m.

The Figures of Merit F_1 and F_2 have been found following the specifications and the procedure described by the Bureau of Indian Standards for the testing of the solar cookers. The average observed values for the Figures of Merit F_1 and F_2 for the BMHSC are 0.12 and 0.47, whereas for the CSC the values are 0.12 and 0.43, respectively. The values specified by the Bureau of Indian Standards for F_1 and F_2 are 0.12 and 0.40, respectively. Hence the developed solar cooker is as per the standards.

4. Energy Savings and Payback Periods

For the calculation of the payback periods the following relation has been used [17].

$$N = \frac{\log\left(\frac{E-M}{a-b}\right) - \log\left(\frac{E-M}{a-b} - C\right)}{\log\left(\frac{1+a}{1+b}\right)} \quad (3)$$

where, a is compound interest rate per annum, b is the inflation rate in energy and maintenance per annum, C is the cost of the cooker (Indian Rupee), E is the money equivalent of energy savings per year (Indian Rupee), M is the maintenance cost per annum (Indian Rupee), and N is the payback period (year).

The payback periods have been calculated on the basis of the fact that there are at least 300 clear days at most of the places having good solar potential in India. Hence assuming that the solar cooker can be used for cooking of two meals a day for about 300 days in a year, it saves 1080 MJ of energy per annum for a family of four persons. As an animal feed cooker the cooker saves 2700 MJ of energy for 4 kg. of animal feed [18]. The energy savings and payback periods have been computed at the following rates *a* = 10%, *b* = 5% and *M* = 5% of the cost of the cookers. The cost of the BMHSC with reflector is 1500/- in Indian Rupee (USD 32.8)and the cost of the CSC is 1760/- in Indian Rupee (USD 38.5). The payback periods have been computed with respect to firewood, charcoal, kerosene, LPG and electric heater. The results have been presented in Table 3.

Table 3. Energy Savings (Indian Rupee) and Payback Periods (years) for the BMHSC and CSC for Various Fuels.

Fuel (Cost-Indian Rupee)	Calorific value (Efficiency %)	Energy Savings (Indian Rupee)		Payback Period (year)			
		Dom-estic	Animal feed	CSC (Dom-estic)	CSC (Animal Feed)	BMHSC (Dom-estic)	BMHSC (Animal Feed)
Firewood ($4.00\ kg^{-1}$)	19.7 MJ/Kg (17.3)	1266	3167	1.68	0.62	1.35	0.53
Charcoal ($8.00\ kg^{-1}$)	29.0 MJ/Kg (28.0)	1063	2658	2.03	0.75	1.63	0.64
Kerosene ($11.00\ L^{-1}$)	38.2 MJ/L (50.0)	622	1555	3.87	1.33	3.04	0.99
LPG ($25.00\ kg^{-1}$)	45.6 MJ/Kg (60.0)	987	2467	2.21	0.81	1.84	0.69
Electricity ($4.00\ kWh^{-1}$)	3.6 MJ/kWh (25.0)	4800	12000	0.41	0.15	0.33	0.10

5. Results and Discussion

It is clear from the Fig. 4 that the rise in water and base plate temperatures for April and June is faster than the water and base plate temperatures for the February as expected. The temperature profiles for the June are slightly better than April but the maximum temperatures are almost the same for water and base plate for the two cases. The temperature of 90℃ has been attained by water in the month of February in two and a half hour whereas for June the time taken is one and a half hour. The stagnation water temperatures are around 94-95℃ for April and June and 90℃ for February. The maximum base plate temperatures are around 110℃ for April and June and 96℃ for February as can be seen from the figure. The temperatures are fairly high looking into the fact that the system is without the reflector. From the various observations carried out on other days it has been found that on clear days the base plate temperatures without load reach around 140°C and with load the temperatures are around 110-120°C.

Fig. 5 and 6 show that the base plate temperatures of the BMHSC and the CSC are initially at a difference of 4-5℃ but at the noon the difference increases to 10℃; higher temperatures correspond to the BMHSC. In Fig. 5 the cookers are without reflectors whereas the observations presented in Fig. 6 are for the cookers with reflector. With a reflector there is sharp rise in the water and base plate temperatures for both the cookers but it is higher for the BMHSC. The water temperatures around 90℃ are reached in one hour for the BMHSC whereas the CSC takes another half an hour to achieve the same temperature. It is quite evident from the figures that the performance of the BMHSC is slightly better than the CSC. There is quicker rise in water and base plate temperatures for the BMHSC.

Further it can be seen from the Table 1 that the mean values for the water temperatures of the BMHSC are greater than the corresponding mean values of the CSC. The observed t-values at 12:00 and 13:00 Indian standard time show that the result is significant somewhat beyond the 0.025 level for directional (one tail) test, whereas at 14:00 Indian standard time the level of significance is beyond 0.005.

The cooking performances of the cooker presented in Table 2 show that it is ideal for boiling, roasting and baking purposes. The food cooked has good taste, aroma, nutritive contents and acceptability. The sensory evaluation tests were conducted by a panel of eight judges on the attributes of texture, flavour, appearance, aroma and mouth feel. For maximum dishes, scores were found to be higher or equal for the solar cooked food as compared to the conventionally cooked food.

It has been observed through animal feed cooking tests that for four kg. of animal feed loaded in the cooker, the cooker without reflector takes around two and a half hour to attain temperatures above 80°C. The highest temperatures are around 87-88°C, which are suitable for slow cooking of animal feed. Four kg. of soaked animal feed can be prepared in around six hours if the cooker is without reflector. With reflector the cooking time is even less. The most important point about the animal feed cooking in BMHSC is that not only the food softens much more than cooked by the conventional methods it also swells much more.

A careful study of Table 3 indicates that the payback periods for the BMHSC are less than those for the CSC and as an animal feed cooker the payback periods are even lower than the domestic use of the cooker. The cost of kerosene and LPG used in the calculations are the subsidized rates as fixed by the government of India, therefore the payback periods would further reduce if the rates of free market were used in the calculations.

6. Conclusions

The on-field comparative thermal performance study of the BMHSC with the CSC shows that the temperature profiles of the BMHSC are slightly better than the CSC. The figures of merit for the BMHSC are found to satisfy the Indian Standards set for the solar cookers. The cooking tests reveal that the cooker is ideal for boiling, roasting and baking purposes as well as for use as an animal feed cooker. The cost of the BMHSC is less than the commercially available solar cooker and therefore the payback periods are also lower. Another advantage with the BMHSC is that it requires negligible maintenance, has long life and there is no hassle of transportation. A remarkable feature of the developed solar cooker is that it can be easily fabricated and repaired by the local labourers, which would help in popularising the use of the solar cookers. Installation of solar cookers at the fields and work sites would generate more work output besides saving fuel and environment.

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Authors

Prof. Prabha Dashora is the Head of the 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. 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. Manjari Gupta and Sunita Mahavar are presently pursuing Ph. D. from the University of Rajasthan, Jaipur.